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Thomas Rinnert

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Par

Thomas RINNERT

PERCEIVING COLLABORATIVE ACTIVITY WITH EXTENDED REALITY

How to improve collaborative work by sharing users' status

Thèse présentée et soutenue à IMT Atlantique, Brest, le 02 juillet 2024

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INTRODUCTION

This dissertation presents work on collaboration and people’s perception of collaborative activity in environments enhanced with Extended Reality (XR) technologies. Collaboration is a crucial field of importance as working together can improve efficiency and productivity. Indeed, by splitting tasks and sharing responsibilities, teams can achieve more in less time and make fewer mistakes, which leads to better outcomes and effectiveness. A team can benefit from all members’s individual skills, each of them might be able to avoid future errors and gain insight from differing perspectives. The baseline of collaborative work is to gather every member in the same place and do tasks together, sharing ideas and capabilities while being physically and/or virtually close to each other.

In general, collaboration within a shared physical workspace proves to be more effective than engaging in remote collaboration [19, 81]. The distinction between collocated and remote collaboration influences teamwork dynamics and the individual capabilities of each team member. Moreover, situations requiring immediate responses involve team members sharing a workspace, whether physically or virtually. The necessity of collaborating while being remote can come from the diversity of places the members of a team are from, simply to save time by removing the need to travel, or because they cannot travel. For example, we have witnessed lockdowns in recent times due to a health crisis (COVID-19).

To enable people to keep working together despite being remote, digital communication devices and technologies provide several levels of presence. With advancements in technology, reduced latency, and increased adoption, the technology is becoming more widespread and of higher quality. However, in both collocated and remote collaborative workspaces, team members often prioritize task-focused activities, at the expense of a comprehensive understanding of overall workspace dynamics resulting in a risk of overlooking implicit cues, such as team members’ fatigue, stress, or mutual misunderstandings. Current remote shared workspaces, despite their advancements, may inadvertently contribute to the oversight of these subtle cues. This dissertation considers improving teamwork with XR technologies regardless of whether it is for teams that physically share the same workplace

or teams exclusively or partially working with remote members.

Previous work within the Computer-Supported Collaborative Work (CSCW) field highlights the potential of overcoming these limitations with XR technologies [45, 135, 159]. These technologies enable collaborators to be partially or fully immersed in a shared workspace. It covers a range of XR workspaces such as environments enhanced by Augmented Reality (AR), fully immersed distant collaborators in Virtual Reality (VR) environments, or Mixed Reality (MR) with collocated users having only part of their collaborators being remote using both AR and VR.

The shared XR environments can be employed to improve mutual understanding, guide, monitor, and coordinate people in many domains such as the Industry of the Future, Defence, Health, and Education [8]. For example, the Industry of the Future can be enhanced by sharing local users' status with remote experts for maintenance and technical operation tasks, decreasing the time and the cost of interventions [29, 73]. As well as for the industry, the proposed solutions can improve remote guidance for maintenance and technical operations for the Defense, but also for mission control to have better monitoring of members of a squad and make better command decisions. Such augmentations can also ease communication during strategy planning [74], or being applied to the task- and team-centred communication among cyber defence analysts and thus improve the collection of information, the identification of current problems the establishment of plans and strategies [35].

In education, augmented classes leverage the integration of virtual objects within real environments, enabling learners to visualise intricate spatial relationships and grasp abstract concepts [28]. These classes provide opportunities for experiencing phenomena that are otherwise unattainable in the physical world [21], facilitating interaction with both two and three-dimensional synthetic objects in mixed reality [162]. Additionally, they support the development of essential skills that may be challenging to cultivate in other technology-enhanced learning environments [146]. XR settings can enhance feedback regarding students' comprehension of lessons for teachers within the context of augmented classes [154]. By introducing these solutions, educators can move beyond relying solely on verbalization, face, and body gestures for assessing learners' understanding. Instead, they gain the capability to obtain feedback on imperceptible measures such as emotions, providing an additional modality for assessing comprehension [59, 97].

Concerning health, the application of XR holds promising potential, both in enhancing the general public's well-being [76] and improving coordination among medical profession-

als [91]. With XR visualisations to share individuals' status information, a new dimension of mutual understanding can be achieved. This approach goes beyond conventional communication methods, providing real-time and contextual insights into the physical and mental states of individuals. In the context of the general public, XR can contribute to fostering a healthier work environment by offering personalized well-being insights. Individuals can receive timely information about factors such as posture, stress levels, and ergonomics, empowering them to make informed decisions that positively impact their overall health and productivity [131, 26]. For medical professionals, the integration of XR facilitates seamless communication and collaboration. Sharing the status of both doctors and patients through XR interfaces mitigates the risk of interpretation errors. This real-time access to comprehensive data ensures that healthcare teams are well-informed, leading to more accurate diagnoses, efficient decision-making, and ultimately, improved patient outcomes. In essence, employing XR to share status-related information can change how to approach well-being at work and medical collaboration.

The proposed solutions of the dissertation are designed to apply to the whole XR field, not specific to AR, VR or MR. Indeed, this dissertation proposes to employ XR technologies to augment individuals with visualisations of their status, encompassing both their performance and well-being. These visualizations aim to enable collaborators to better understand augmented individuals, whether their task-related status or personal feelings, fostering improved mutual assistance, and empowering collaborators to respond effectively. Throughout this dissertation, the potential evolutions of teamwork are illustrated through example use cases, centred on symmetric work and task allocation.

1.1 Motivations

Collaboration often faces major obstacles as people work together, whether fully collocated or at least partially distributed, by missing implicit indications such as team members' fatigue, stress or mutual misunderstanding. Moreover, collaboration becomes more difficult in a distributed context, and in the worst case, these missed implicit indications can cause the failure of the collaborative task. Thus, addressing these numerous and complex challenges is imperative before achieving the full potential of XR in supporting collaboration. Additionally, XR systems need to fill the gap between being physically present and being remote. XR systems must improve collaboration even further, acknowledging that a shared physical workspace holds irreplaceable value [70], and beyond being

able to see them, gaining a deeper understanding of team members is necessary for this improvement. This understanding of both what and how they are doing helps to understand collaborators: there is thus a need to be able to read their performance in past activities and how well they are coping with work. These past and current performances can be measured in several ways depending on the task allocated to the group, and the well-being of collaborators although need to be interpreted from various modalities, such as individuals' status, gestures and facial expressions.

These insights and the challenges they pose reveal multiple research directions. First, investigating new network architecture would ease the deployment of complex distributed teams, whether it concerns large groups such as Virtual Reality Massive Multiplayer Online (VRMMO) games or social gatherings (e.g. IEEE VR conferences during the pandemic), groups with multiple non-exclusive roles involved and how people handle interactions inside such a rich role diversity collaborative workspace, or groups having different augmentative or immersive technologies (e.g. a team evolving in a real workspace distant members having a 3D reconstruction of that environment).

Second, the exploration of defining, measuring, and presenting performance has been ongoing [20, 45, 135]. Despite the extensive exploration, there remains room for refinement in all three aspects. The definition of performance is influenced by the applicative context, impacting both its measurement and subsequent presentation. There is potential for exploring innovative approaches to measure performance-related information and establish effective presentation methods, initially within experimental contexts and subsequently applying these approaches to real-world applicative scenarios.

The third aspect involves enhancing the measurement of collaborators' status, by refining the collection and abstraction of physiological data into more comprehensive labels to provide a clearer understanding of their feelings. For instance, some research gauged cognitive workload by monitoring both blinking frequency and pupil dilation [93].

Lastly, investigating the analysis of hands, arms, full-body gestures, and facial expressions can enhance the understanding of other team members, whether it relies on individual interpretations or those generated by Artificial Intelligence (AI) algorithms [1, 2, 84]. It is important to note that this is not an exhaustive list but rather a focus on some of the current most crucial issues [45, 135].

To contribute to this research field, this dissertation focuses on investigating how to enhance the collaborative experience and deepen the understanding of each other's actions, behaviours, and feelings. This is achieved by proposing innovative approaches in

XR to provide users with information about their team, including members' performance and internal status such as stress. This focus was motivated by the importance of understanding each other in a simple team before even considering tackling the complex collaborative scenarios presented above. Addressing the users' status, various methods can be employed to gather information such as body temperature or heart rate. As the research in gathering and automatically interpreting performance and physiological data is very prolific [1, 2, 36, 37, 84, 92, 93], investigating how to present such data is an important approach to contribute the Extended Reality Computer-Supported Collaborative Work (XR CSCW) field.

This dissertation proposes to present this data through visually augmenting collaborators' bodies or avatars with performance and status information. The NASA MATB-II is a well-studied system with easily measurable user performance [129], and it is used to evaluate these propositions through experimentations. Indeed, this dissertation primarily focuses on the presentation of users' status, recognizing that addressing the methods for gathering and interpreting such data is an expansive topic that lies beyond its scope. Teaming is a term that more precisely refers to the type of collaboration addressed in this manuscript, whether it is a team of the same level of workers looking after each other, or a team of workers under a supervisor. In those kinds of teams, members have common progress, a team performance that can be measured and improved. This investigation rather focuses on synchronous collaboration than asynchronous although, in terms of location, it can be applied to both collocated teams and teams with remote members.

In an ideal augmented workspace, pertinent information regarding each collaborator's performance and well-being would be available. In other words, team members performing adequately would not have visible performance augmentations. However, individuals encountering challenges in maintaining their usual performance level would display augmentations indicating their need for assistance. High-performing individuals with no immediate tasks at hand would also have an augmentation, signalling to those responsible for task allocation that they are available for additional work. This envisioning of an augmented workspace aims to provide clear and context-sensitive indicators, ensuring seamless communication and coordination among team members. Incorporating augmentations that provide insights into individuals' well-being—spanning stress, fatigue, cognitive workload, and beyond—serves as a valuable preventative measure. This approach aids in discerning when assistance may be required even before a noticeable decline in performance. Particularly in task allocation, being aware of a team member's well-being

is crucial; assigning excessive work to someone not in optimal health can lead to increased errors and potential failures. Eventually, the prediction of the evolution of the inner status of workers would further increase the overall team performance and individual well-being. In summary, such a system would enable better mutual understanding and thus lead to better collaborative outcomes.

1.2 Research questions

This investigation addresses research questions that would contribute to computer-supported collaborative work and extended reality fields. Throughout the manuscript is presented how those questions were addressed and which solutions were chosen to answer them.

RQ1 – How does sharing users’ status with XR improve collaboration? The initial requirement to enhance collaborative work with XR involved an exploration of the augmentations that could be presented among collaborators and an understanding of how they impacted the collaborative experience. The first study within this dissertation aims to determine whether the perception of users’ status can contribute to improved mutual assistance and overall team performance. In the course of these investigations, the research discerns which aspects of user status data are most valuable for detecting and characterizing the need for assistance, ultimately leading to enhanced team performance.

RQ2 – What are the elements helping leaders to understand their team members’ status and how to present them? Addressing this research question could for example improve the detection and characterisation of an individual’s need for help, and sharing the status of workers could potentially help a team leader to better allocate tasks to their team. We thus implemented a use case for experimental purposes, involving a team leader assigning tasks to operators, and asking the team leader to optimize the overall team performance. Again, several feedback components were developed and the relevance of each of them was investigated. A step further was to provide feedback on the potential evolution of the status and study how it helps team leaders make better decisions.

RQ3 – How should the data be abstracted to better understand the team members’ status? Aligned with the preceding research questions, this dissertation investigates the optimal level of detail and presentation style for enhancing teamwork through shared information. The investigation considered whether raw data from sensors and sys-

tem attributes should be directly shared, or if it would be more beneficial to abstract it behind discrete "good" and "bad" levels. The investigations further studied the potential advantages of a hybrid approach, combining both strategies. This critical aspect has been thoroughly addressed throughout the entirety of this dissertation, underscoring its significance. However, further exploration and refinement are required, acknowledging the complexity and the context-dependence of potential solutions.

1.3 Contributions / Methodology

To improve the level of awareness for collaborators, this investigation proposes to augment them with information cues about their emotional state and physiological state, and with information cues about the collaborative task they have to achieve. Adequate visual metaphors of team members' status and task performance are proposed to understand the current activities from passive monitoring of their actions and behaviours. These visual metaphors are validated through a set of user studies to determine the effectiveness of providing such indications to detect the need for help and balance workload when allocating tasks to team members.

1.3.1 Theoretical

This dissertation explores various visual solutions aimed at enhancing teamwork, addressing key aspects while acknowledging that the coverage is non-exhaustive. The main focus is on improving mutual understanding among team members by studying the sharing of feedback on their status, aiming to facilitate the detection of needs for assistance. Additionally, the dissertation delves into the impact of sharing both performance and inner states on the overall performance of teamwork. In continuous collaboration scenarios, where team members can interact with each other's work, the dissertation explores the benefits of sharing current performance status and progression information. Furthermore, the dissertation examines the implications of providing predictions about the evolution of team members' status to team leaders, exploring its influence on performance and management strategies. For the presentation style of visual indicators, this dissertation suggests considering both ends of the literal-symbolic axis. The presentation of literal and non-abstracted data provides precision for easily understandable measures, while symbols can offer clarity or abstraction for more complex values. The dissertation addresses the

challenge of determining the optimal level of detail when abstracting information, with fewer details resulting in greater abstraction. It proposes initial steps toward finding an optimal level within this context.

1.3.2 Technical

XR visualization techniques were implemented to present the performance and inner status of users, enabling the sharing of this information with others. Proposed visualizations were regrouped and presented on a body-relative panel, situated on the forearm of users for convenient reference, akin to a smartwatch. Alternatively, some visualizations were distributed across all team members on floating panels. The proposed visualizations underwent examination at various levels of abstraction. To evaluate these propositions, an experimental platform was modelled and prototyped within an immersive environment, featuring an adapted NASA MATB-II system and virtual worker models for studying team management. An initial prototype was provided by Jamie Gower, PhD student at UniSA, containing a single-user version of the VR adaptation of MATB-II. The experimental platform, available as a research artifact, can be accessed at https://github.com/ThomasRinnert/MATB-II_CollabVR, showcasing both symmetric collaboration and team management scenes. All evaluated visualizations are implemented and included in this repository.

1.3.3 Empirical

The contributions outlined in this dissertation underwent rigorous evaluation via user studies. The effectiveness of providing task status feedback to enhance the detection of when a collaborator requires assistance was validated in the initial study detailed in Chapter 3. Additionally, this study confirmed team members' preference for focusing on current performance status rather than progression information. The positive impact of sharing the inner status of team members on team performance was demonstrated through a second study, as elaborated in Chapter 4. This investigation also confirmed the team leaders' inclination toward a higher level of abstraction in interpreting their team members' inner status. Participant feedback from this study proved the advantages of both literal and symbolic presentations, emphasizing the importance of providing both raw and abstract information to meet diverse preferences. Building upon these contributions, this dissertation introduces two further enhancements for team performance. The findings from

a third study, detailed in Chapter 5, validated that providing a prediction of the evolution of team members' inner status positively influenced team performance. Additionally, this study also validated that a higher precision in the inner status of team members assists leaders in optimizing team performance.

1.4 Thesis structure

This dissertation starts with a chapter reviewing the state of the art on the perception of XR collaboration. Chapter 3 presents the contributions addressing **RQ1** with synchronous and symmetric collaboration, assessing the relevance of providing status indicators to each other. Chapter 4 covers this dissertation's first contributions to team management and how to help team leaders allocate work, addressing **RQ2**. Chapter 5 describes the investigation into team management with a focus on the prediction of internal status, addressing both **RQ2** and **RQ3**. The dissertation ends with a final chapter that brings a conclusion and proposes potential future work.

STATE OF THE ART

The chapter presents a review of the state of the art on Human Perception, Collaboration and Extended Reality. The first step is to understand those fields to uncover where improvement is needed. Each of them can also be broken down into more specific topics as can be seen in Figure 2.1.

Human Perception is a wide field of research [24]. This dissertation addresses collaboration, focusing on awareness rather than the whole human perception range. Awareness encompasses both the process of gathering environmental information through sensorial channels and the cognitive constructions resulting from it [108]. This chapter will present the current related work on how to convey awareness and how to improve collaboration.

Collaboration itself is also a wide field of research [121]. This literature review focuses on XR-applicable research to augment existing shared workspaces instead of proposing new collaboration methods. The "metaverse way" of collaboration is still being explored, and yet despite progress, some people may never transition from physically shared workspaces (e.g. open spaces, factories, etc.) and audio-video conferencing to a fully immersive collaborative environment.

Extended Reality (XR) is a way to improve collaboration by conveying and supporting shared awareness more efficiently than in classic shared workspaces [107]. As wide as the XR field is, this dissertation focuses on augmenting workspaces, whether physical or virtual. While augmentations to a user's environment can be conveyed through various sensory channels [148], this chapter predominantly examines literature focused on XR visual augmentations. The reported research works focus on aspects of XR that are directly applicable to and beneficial for real and physical work environments.

This chapter introduces the field of Extended Reality in the first section. The second section presents related work on Collaborative XR. The third section addresses Awareness in collaborative settings. The fourth section presents how information can be displayed in terms of placement and abstraction. The chapter ends with a discussion on the state-of-the-art limitations and areas of interest tackled in the next chapters.

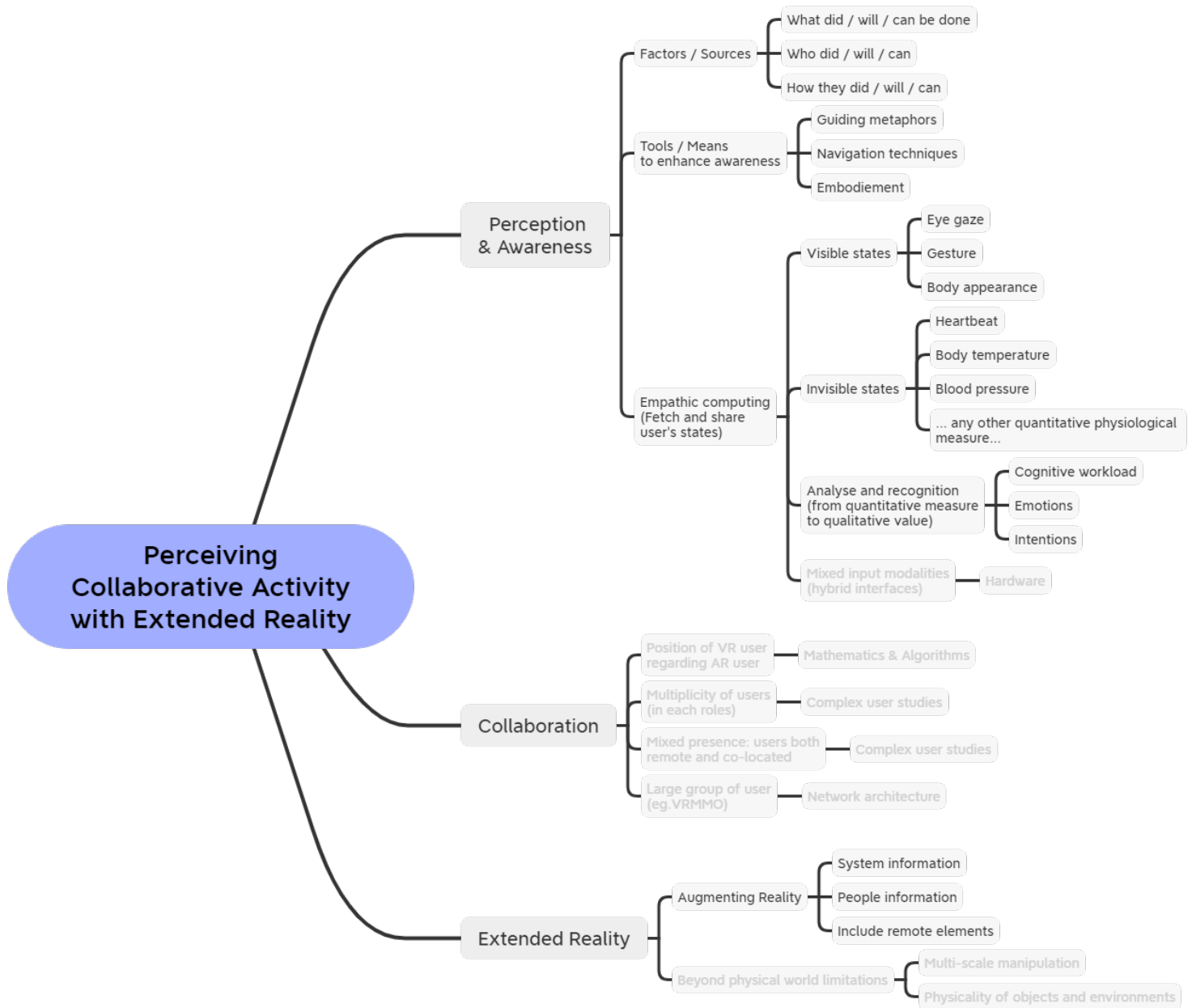


Figure 2.1 – By breaking down the thesis title, three major axes are identified: Perception & Awareness, Collaboration, and Extended Reality. When studying these subjects, some research directions were identified but considered out of scope to improve the awareness of collaboration in XR settings. The excluded yet promising research directions are written on the figure in a grey font. For example, while the deployment of collaborative environments was essential to evaluate the propositions presented in the following chapters, the exploration of new network architectures was not within the scope of this study.

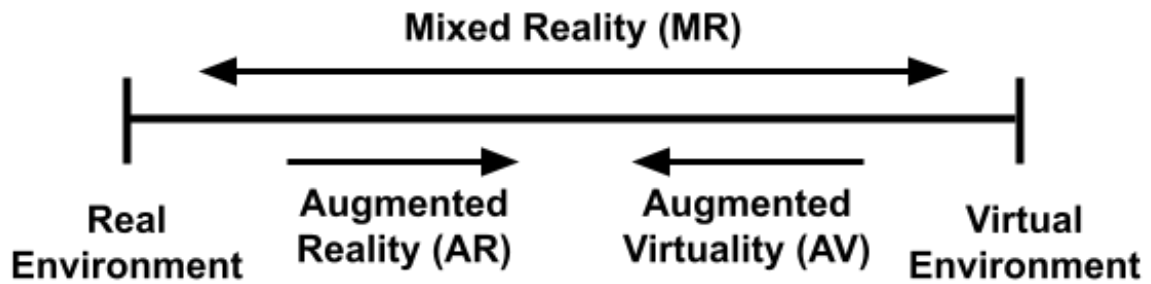


Figure 2.2 – Milgram et al. proposed classification immersive levels.

2.1 Extended Reality

Extended Reality (XR) is a wide field of research addressing augmented and immersive technologies [45, 135], whether it is by slightly augmenting the real world with sensory artifacts (eg. displaying an overlay on someone’s vision to share information) or by fully replacing sensory channels with computer-simulated information (eg. a head-mounted display putting two screens in front of someone’s eye). Milgram et al. [105] placed these different levels of immersion on the reality-virtuality continuum (see Figure 2.2). This classification is often modified to include more recent topics, for example, Skarbez et al. proposed to extend this continuum to a 3D space along world knowledge, spatial presence, and coherence to refer to the whole space as "Mixed Reality" [139].

Acknowledging there have been many different acronyms and terms appearing, including AR, VR, MR, XR, and most recently Apple’s spatial computing [6], the fundamental goal of all these technologies together is to enhance the user’s perceptions of the world (real or virtual) with artifacts, interactive or not. As such, the technologies and research have matured to a point that experiences and problems that exist across the whole continuum - or large sections of it - can be explored. Whilst this chapter will explore related work across the different individual areas of AR, VR, MR, and XR, for this dissertation, Extended Reality will be used to refer to the immersive technologies along Milgram’s spectrum, from augmented reality to augmented virtuality. Indeed, XR refers to the ability to extend the user’s space, merging and aligning virtual content to real objects using real-time rendering and supporting real-time interaction [107]. XR also allows users to interact at multiple scales [112, 115, 116, 117, 163] and to navigate through space and time [95, 147]. The use of XR can be combined with Computer-Supported Cooperative Work (CSCW), enabling XR collaborative environments [45, 135]. Similar to CSCW, the

use of XR collaborative environments can improve user performance and learnability as compared to traditional tools [107, 153].

Either aimed at recreating the real world into a new virtual world or overlaying reality with virtual content, several technologies enable the use of XR by replacing or overlapping virtual and real content. While handheld devices allow the use of AR [22], non-body-mounted systems enable users to perceive XR content with their hands-free: from Spatial Augmented Reality (SAR) environments on the AR end of the XR continuum [23], to CAVE Automatic Virtual Environments (CAVE) on its VR end [33]. On their side, Head-Mounted Displays (HMD) can add or replace perceptive information being worn as a headset. HMD users can experience Optical See-Through (OST) AR with semi-transparent lenses, overlaying visual information with computer-generated content [46]. Other HMDs enable users to experience VR by having two screens replacing their whole field of view [103], and some of those headsets offer to switch from VR to Video See-Through (VST) AR, displaying the real world recreated by computer-vision [80]. Using HMD enables users to experience a larger part of the XR continuum, the limited width of the field of view can be addressed by designing a denser workspace, and the tracking of the user within the environment has been widely tackled over the years [4, 106, 144].

2.2 Collaborative XR

Collaboration involves multiple entities working together to accomplish a task or reach a common objective [101]. The collective is often stronger than the individual: teams can take on more involved work than individuals because team members can combine their diverse, complementary capabilities to provide backup behaviour, monitor one another to reduce errors and shift the workload as needed [60]. Given the unique nature of each team, it is essential to account for factors such as task interdependence, context, team purpose, and composition to understand relevant team dynamics and outcomes. While the literature lacks a unified definition of teamwork, its essence lies in various team mechanisms, including shared cognition, cohesion, process dynamics, and interventions such as leadership and team training that shape team processes and subsequent effectiveness [82]. Teams are becoming more interprofessional [48], interdisciplinary [65, 142], and cross-cultural [50]. Across most disciplines, research is increasingly conducted in teams, leading to higher impact and innovation [155]. Consequently, many fields are actively seeking to understand how to promote and support effective teamwork to enhance team performance,

foster innovation, and facilitate adaptation within their respective domains. The lack of consensus on the precise factors that constitute teamwork has led to diverse methods for teamwork measurement, each with specific strengths and limitations [126]:

- Self-reported measures are straightforward to administer and are useful for assessing affective teamwork properties like trust [71]. However, they provide static data at a single point in time and are subject to individual biases. Aggregating individual ratings to the team level can be challenging.
- Observer-rated measures can evaluate team performance more objectively using behaviorally anchored scales with concrete examples [111]. Nevertheless, this approach is time-consuming, and observer ratings can be influenced by biases such as primacy and recency effects. Aggregating individual ratings to the team level may also pose challenges.
- Event-based measurement links assessments directly to objectives and allows for the observation of complex performance scenarios [51]. However, developing scenario-specific checklists is labour-intensive, and focusing on specific events may lead observers to overlook other important teamwork behaviours.
- Automated measures offer unbiased and unobtrusive assessments of team performance, minimizing error and decreasing the demand for experimenter resources [31]. They provide real-time, dynamic performance data but face challenges in establishing psychometric validity. Using automated measures in conjunction with other methods is advisable to enhance measurement reliability.

Teams vary across contexts, but insights gained from one context can provide a broader understanding of teams in general. In some cases, teams operating in different contexts exhibit strong similarities. For example, literature discusses transportable teamwork competencies [128]: *Coordination*, *Communication* and *Adaptability*. *Coordination* involves organizing individuals' skills, behaviours, and knowledge to achieve a common goal. *Communication* involves the exchange of information among teammates in various forms. Quality of communication is often emphasized over frequency [99], highlighting the importance of clear and understandable communication practices [48]. *Adaptability* is a key skill within teams, characterized by the ability to adjust behaviours and strategies in response to changing circumstances. This skill is considered universally effective in enhancing team performance [40]. Engaging in team reflections or debriefs can aid team members in understanding how to adapt their behaviours for future scenarios [3].

When team members perceive that the demands of their environment exceed their

available resources, they experience stress, which can negatively affect physiological, psychological, behavioural, and social outcomes [90, 127]. Although stress can make team members more receptive to the inputs of others during task execution [44], its overall impact can be detrimental. Extensive research supports that teams can experience significant challenges and even self-destruct in highly stressful situations [27, 39, 41]. Team coordination strategies can shift from explicit to implicit coordination as workload increases [136]. Explicit coordination involves transferring information and resources in response to requests and using communication messages to coordinate actions. In contrast, implicit coordination relies on team members' anticipation of each other's information and resource needs, often based on shared mental models or a common understanding of the situation. While implicit coordination is generally less time-consuming and resource-intensive than explicit coordination, it requires accurate and shared mental models among team members [150]. The challenge of structuring teams under stress does not have a one-size-fits-all solution [38]. Theoretical and empirical complexities arise from the numerous control mechanisms teams can utilize to maintain performance and manage workload under simultaneous external and internal stressors. As conditions become more stressful, teams often shift toward leader-directed coordination to sustain performance levels [136].

While roles and responsibilities within collaborative endeavours can often be shared and dynamically reassigned, some settings necessitate centralized team management. Individuals responsible for team management must provide leadership, encompassing various functions with significant organisational implications. Such functions include making strategic decisions, engaging with external stakeholders, managing human resources, motivating and influencing team members, handling information, overseeing operations and administration, addressing social and ethical concerns, and managing conflicting demands [137]. Traditionally, leadership theory and research predominantly focused on singular, formal leaders and their impact within organizations until the end of the 20th century [11]. However, leadership dynamics have evolved to accommodate the complexity of modern teams, where shared leadership models are increasingly recognized and studied [152].

Several factors affecting the collaboration quality have been identified as Radu et al. show in their survey [121]. The first identified factor is the need for collaborators to be aware of others' attention and activities. Other factors reflect the need for collaborators to be aware of the past, their need for attention and instruction coordination, and their need for ownership and interactions with a space or an object while sharing the same workspace.

Additionally, organizations, team leaders, and teammates must create environments where psychological safety can flourish and be a mechanism to resolve conflicts, ensure safety, mitigate errors, learn, and improve performance [53]. Acknowledging the vast scope of collaboration research, this dissertation explores XR’s contributions to various collaborative dimensions proposed by Marques et al. [100]. The taxonomy encompasses ten dimensions, each shedding light on different aspects of collaborative XR:

Team: Along this dimension, the taxonomy characterises collaborative XR on its physical distribution (i.e. if the team is fully, partially or not colocated at all), the roles nature and structure adopted (i.e. if the team is multidisciplinary or not, and if responsibilities are fixed or can be exchanged), the number of entities constituting the team, its lifespan and turnover, and its usage of technology.

Time: This dimension describes the collaborative setting’s synchronicity, duration and predictability. While XR asynchronous collaboration has immense potential, eg. with the use of XR ubiquitous computing to augment the entire world [132] collaboratively, considering the scope of the PhD works, this literature review will focus on continuous and synchronous collaboration.

Task: This dimension addresses the type and interdependence of collaborative tasks, as well as the nature of the environment where the tasks are to be performed.

Communication: Collaborative XR is categorized in this dimension on the structure and mode employed for communication. Categorization here goes further by describing the intent, frequency and duration of said communication.

Scene capture and tracking: This dimension describes the technological aspects of collaborative XR, whether for tracking, scene capture, available viewpoints inside the environment or how the shared scene is updated over the network.

Shared Context Sources: This dimension focuses on shared content production and collaboration’s impact on the environment.

Level of user actuation: This dimension describes the abilities of users and the symmetry of their roles and capabilities. K. Schmidt [133, 134] addressed this topic by separating collaborative work into three categories: *augmentative*, where everyone has the same interaction capabilities; *integrative*, where people have complementary interaction capabilities; and *debative*, where discussion and strategy are the main parts of the collaborative activity.

Output and augmentations: This dimension categorizes the perceptual information collaborators can produce and how those modalities interact.

Input modalities: This dimension refers to the sensory channels immersive technology employed by users provides them and how those modalities interact.

Research: This last dimension relates the domains of application of a research a collaborative XR contribution, whether abstract or applied research and the evaluation modes employed.

Using a collaborative virtual environment enables the use of XR in a shared workspace, even in a remote collaboration context. Existing applications include augmented classes in Education and Training [28], XR-guided surgery in Health [141], VR multiplayer games in Entertainment [122], remote expert guidance in Industry [29], and integration of Building Information Modeling in Architecture [102]. However, there remains a lack of perception regarding other users' activity and emotional states [15]. This dissertation addresses this gap by proposing enhancements in mutual perception and understanding within XR environments. While the implementation and architecture of such environments face engineering challenges [42, 156], they can support cooperative interactions [61, 98, 157], and teleoperations [30]. They also facilitate access to shared workspaces, accommodating users regardless of immersive technology. For example, remote users with head-mounted displays (HMDs) can join collocated AR users' environment [88], and a single HMD user can share their virtual environment with AR users using floor projection and mobile displays [62]. Additionally, remote guidance of fully immersed users from a 2D interface is feasible [78] as well as sharing one's surrounding environments through 360° live panoramas to HMD users [87]. The propositions in the next chapters consider this diversity of XR settings and usages, aiming to enhance comprehensive sharing among users [96]. The next section will delve into related work on the perception of collaborative activity and mutual understanding in XR environments to contextualise further.

2.3 Awareness of collaboration and what to convey

Yang et al. investigated remote immersive collaboration: “*When people collaborate remotely using desktop interfaces they no longer feel like they are sharing the same space. This limitation may be overcome through collaboration in immersive environments, which simulate the physical in-person experience.*” [159]. This section overviews how related works suggest simulating this in-person experience, and how XR enhances the understanding of collaborative activity.

2.3.1 Awareness of collaboration

The notion of awareness refers to the knowledge and understanding of self and the surrounding environment. This subject has been widely studied and characterized, whether by examining how people interact with each other and with the environment [16], by assessing the proximity between the perceptive elements and their observer [85], or by classifying the perceptive elements according to how they contribute to creating awareness [64].

Steve Benford and Lennart Fahlén propose a definition of awareness based on set theory principles [16] (see Figure 2.3 Top). According to their framework, awareness is structured into layers of sets. The first layer encompasses the concept of *aura*, which represents the spatial boundaries and capabilities of an entity. Entities interact by intersecting multiple *auras* through one or more *mediums*. The second layer hosts the *focus* and the *nimbus* sets. The *focus* denotes an entity's awareness of others, while the *nimbus* represents the awareness that other entities have of a single one. These sets can be dynamically manipulated using *adapters*, metaphorical tools that modify or group them into common sub-spaces. In summary, awareness, as defined by Benford and Fahlén, is the capacity to comprehend and regulate interactions, leveraging the interplay of *auras*, *focuses*, and *nimbuses*.

Morgan Le Chénéchal proposes a taxonomy of awareness categorizing it into distinct levels based on the proximity of elements to the observer [85] (see Figure 2.3 Middle). These levels serve as a structured framework for understanding the various dimensions of awareness in interactive environments. The taxonomy begins with the *Object* level, focusing on the selectability, ownership, and modifiability of individual objects. Moving up the hierarchy, the *Task* level examines participation and status within ongoing tasks. The *World* level expands the scope to spatial information, considering the locations of objects and users. At the *Group* level, attention shifts to group dynamics, including member actions, positions, and capabilities. The *Social* level explores communication channels available among participants. Finally, the *System* level encompasses awareness of system states, such as stability, network latency, and performance. This taxonomy provides a comprehensive framework for analyzing and understanding awareness dynamics across different levels of interaction.

Carl Gutwin and Saul Greenberg define awareness as the comprehensive understanding and knowledge necessary to answer key questions about collaborative tasks [64] (see Figure 2.3 Bottom). These questions, referred to as "awareness questions" in this dis-

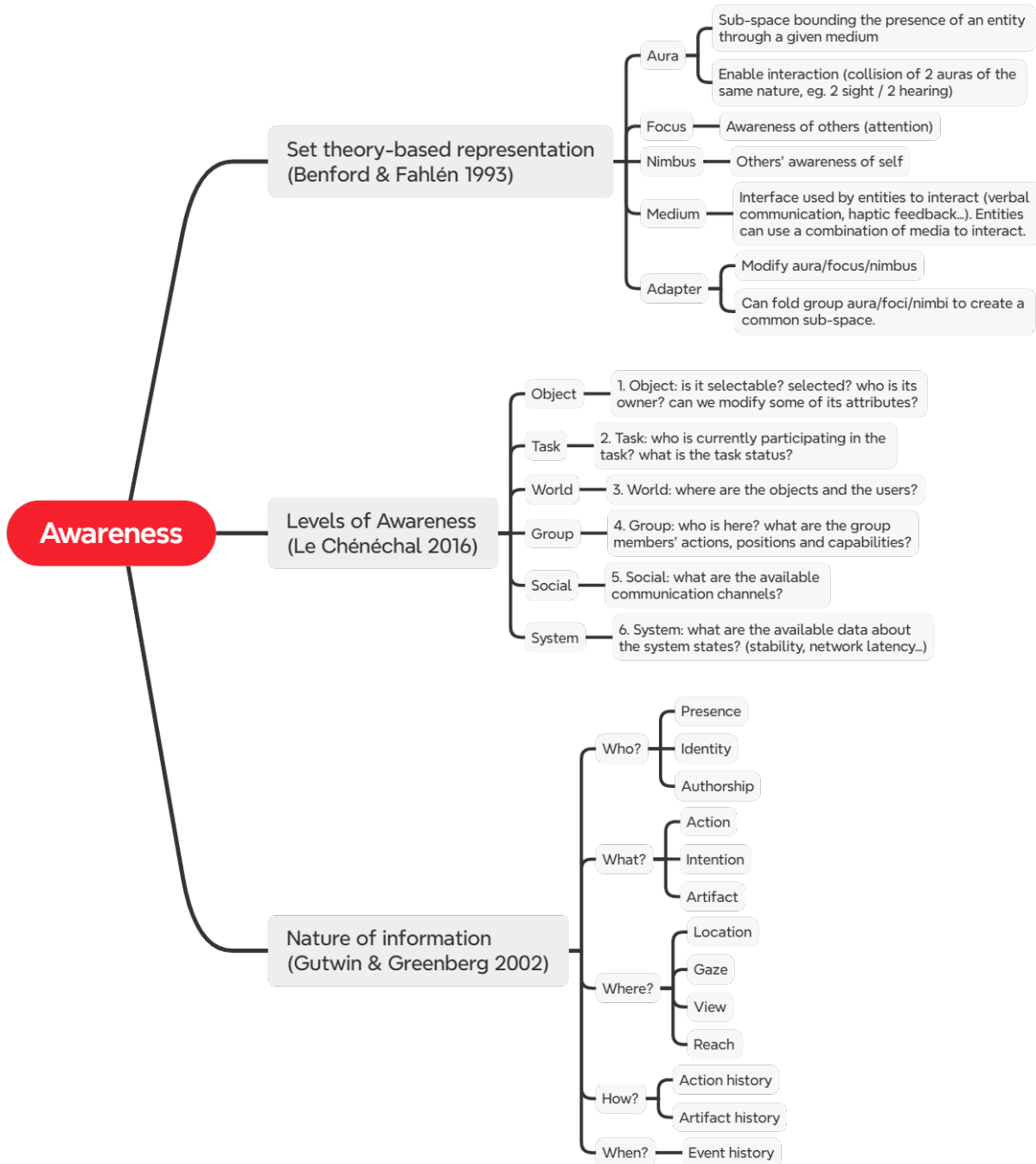


Figure 2.3 – Three awareness characterizations: Steve Benford and Lennart Fahlén [16], Morgan Le Chénéchal [85], and Carl Gutwin and Saul Greenberg [64].

sertation, encompass inquiries into the *Who*, *What*, *How*, *Where*, and *When* aspects of task-related activities. The accessibility of information within a shared environment is contingent upon the nature of these awareness questions:

- *Who* questions focus on presence, identity, and authorship, such as determining if anyone is present, identifying individuals, or ascertaining who is responsible for a particular action.
- *What* questions delve into actions, intentions, and involved artifacts, seeking to understand the nature of ongoing activities, the underlying motivations, and the objects or artifacts involved.
- *Where* questions revolve around locations, gazes, views, and reaches, providing insights into the spatial context of activities, the direction of participants' gazes, their field of vision, and their physical reach.
- *How* questions involve exploring the process history, detailing the impact of actions on objects and individuals, and understanding the causal relationships underlying events.
- *When* questions establish an event history, linking all information to time and providing temporal context for actions and events.

This framework offers a comprehensive approach to understanding the multifaceted nature of awareness in collaborative environments, guiding the accessibility and dissemination of relevant information for effective teamwork.

Awareness thus encompasses a comprehensive understanding of interactions, spatial dynamics, and information cues. It involves perceiving and regulating interactions through spatial boundaries and capabilities, categorizing awareness levels based on proximity, and addressing key questions about task-related activities such as presence, actions, spatial context, process history, and temporal aspects. When exploring awareness in collaborative environments, the perceptive elements enable people to be aware of the collaborative activity. Particularly relevant in work-related contexts, workspace awareness is the knowledge required to operate or maintain a system, and the up-to-the-moment understanding of another person's actions, this knowledge is mainly created through interaction with the environment and other people in it [135]. However, perceiving collaborative activity goes beyond just understanding people's actions but also how emotional states, motivations, and methods of interaction influence collaboration. Taking this understanding a step further, the field of empathic computing explores how technology can increase empathy and create a deeper shared understanding among collaborators [113].

Irlitti et al. showed that capturing a team member’s active and passive actions and behaviours would provide other team members and leaders with a much broader range of information when confronted with decision-making [75]. This chapter thus presents related work on workspace awareness and empathic computing fields, laying the groundwork for exploring the ‘awareness of collaboration’ in this dissertation. For instance, Yang et al. [159] investigated collaborative sensemaking with groups of users in XR, their findings suggest several positive outcomes and potential advantages of XR to improve the awareness of collaboration.

2.3.2 Conveying awareness cues with XR

Related works explore several ways to improve the awareness of collaboration with XR. First, for remote collaboration, XR must recreate perceptive elements to get closer to a physically colocated situation. XR systems thus provide verbal communication [49, 158], embody people with realistic avatars [12, 161] to represent hands, arms and full body gestures [13, 73, 86, 114, 140]. Hollan and Stornetta wrote that XR could not recreate a perfect clone of reality, so immersive environments must be created as more than just a copy of reality [70], they must augment the reality. Moreover, improving awareness goes beyond just perceiving people’s actions, but requires more information about how they feel, why they acted, how they did what they did, and any other elements that may influence collaboration.

A first approach to enhancing mutual understanding in XR workspaces involves sharing each other’s visual perspective. Collaborators can present their view frustum as a cone or pyramid [29] and their eye gaze as seeable rays [47]. While sharing gaze improves awareness, it may differ from the actual focus, such as when orators use visual support during presentations.

Indeed, related works propose methods for referring to the focus of collaborative activity. Visual representations like pointers clarify what individuals want to designate with a seeable ray [43, 63]. While pointers increase mutual understanding and emphasize the user’s focus, they require active interaction.

Another approach involves adding modalities to communication. Some XR systems allow users to sketch on surfaces or mid-air while speaking [73, 143], supporting verbal statements. Again, while these methods enhance mutual understanding, they necessitate action from collaborators.

A more in-depth mutual understanding is achieved by passively sharing emotions [1,

66, 109] and physiological data [66, 77, 113] among collaborators. Emotions can be presented with a label, body movements or facial expressions while physiological data are more implicit by nature and need more complex indicators. For example, Dey et al. shared the heart rate between two participants with a heart icon in their field of view [36] and later shared the heart rate between two participants through controllers' vibration [37]. On their side, Luong et al. gathered mental workload by integrating sensors in a head-mounted display, and ocular activity was the best indirect indicator of mental workload [93]. They then showed that designing complex training scenarios with multiple parallel tasks while modulating the user's mental workload over time was possible [92].

Collectively, the highlighted research demonstrates that the provision of various awareness cues correlates positively with enhanced task performance, user comfort, sense of presence, and spatial perception within XR environments. Furthermore, it is noted that the integration of multiple awareness cues through multimodal approaches, as demonstrated by some studies [63, 109], serves to complement rather than replace existing cues.

2.4 Displaying XR information

In terms of information placement and presentation within shared workspaces, considerations often revolve around situating information either outside or inside the workspace and presenting it in either literal (raw data) or symbolic (abstracted) forms [64, 135]. Given the overarching objective of this dissertation to enhance teamwork within shared workspaces, this literature review will focus specifically on workspace-situated information. Indeed, it is worth noting that various approaches exist for dispatching and presenting information within such environments.

Three primary categories of placement for information within virtual environments were considered: fixed, movable, and body-relative. In the fixed placement approach, information is displayed at predetermined locations within the virtual environment, ensuring users can easily locate it when needed [106, 119, 120]. Conversely, in a movable placement strategy, information is presented as virtual artifacts that users can move, resize, enable, or dispose of as needed, providing flexibility and adaptability [25]. In a body-relative placement configuration, information is presented attached to the user's body, such as on their wrist or fingers, akin to a smartwatch interface [25, 151]. Existing implementations of these placement strategies can be observed in VR applications like EchoVR [124] and Zenith [122] (see Figure. 2.4), as well as in academic research projects [14, 77, 130, 135],

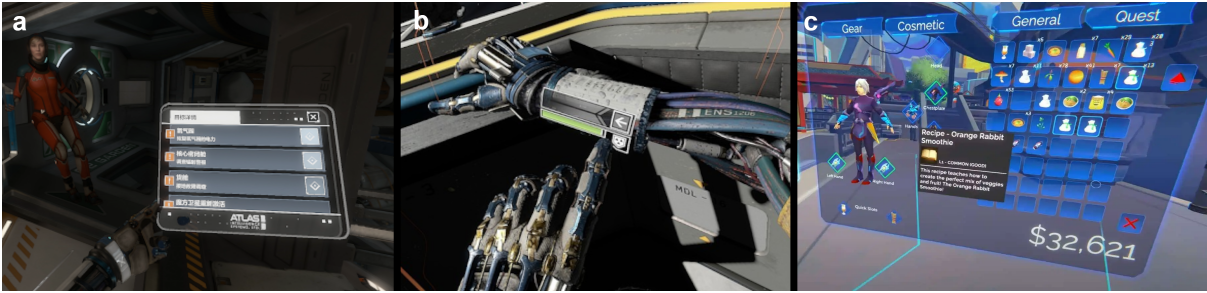


Figure 2.4 – Samples of information placements in VR games:

- a) a movable artifact (tablet) in Echo VR (© 2024 Meta);
- b) a body-relative panel (attached to the wrist) also in Echo VR (© 2024 Meta);
- c) a fixed panel when opening menus in Zenith (© 2020s Zenith Games).

such as Tablet Menus and Tulip Menus proposed by Bowman and Wingrave [25] (see Figure. 2.5).

The presentation of information within collaborative environments can take various forms, ranging from literal representations of raw data to more abstract symbolic depictions, as discussed in previous literature [64, 135]. However, it is essential to recognize that the abstraction of data is not a binary choice but rather a continuum, representing the degree to which information deviates from its raw form. This abstraction level is influenced by the inherent nature of the information being conveyed, as highlighted in existing research [20, 45, 135]. While this dissertation aims to provide a comprehensive overview of the principles underlying collaboration in shared workspaces, readers must understand that the optimal abstraction level of information may vary depending on the specific context and application. As such, when transferring the findings of this dissertation into practical use cases, it becomes necessary to tailor the abstraction level of shared information accordingly. This adaptive approach will ensure that the information presented remains relevant and useful to the end-users, facilitating effective collaboration and decision-making in real-world scenarios.

2.5 Summary of the state of the art

In collaborative settings, understanding one’s collaborators and their actions is crucial, necessitating a high awareness of collaboration. This process hinges on shared environments providing perceptual elements, which may range from natural perceptions such as visible body language and gestures to internal information accessible only through XR,

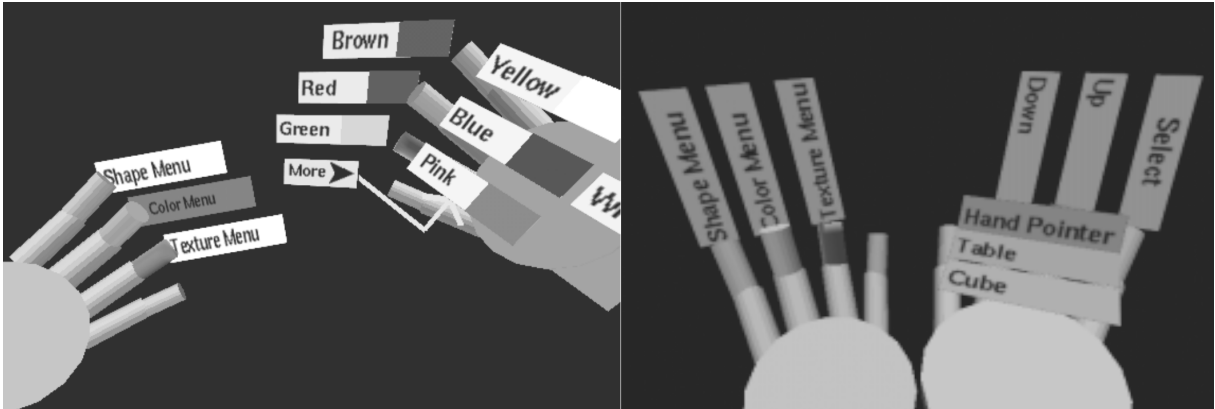


Figure 2.5 – Tulip Menus proposed by Bowman and Wingrave. Menu items are situated on the fingers of a user, a menu is chosen by pinching the thumb to the appropriate finger. The top level of the menu hierarchy (menu titles) is displayed on the non-dominant hand, and the second level of the hierarchy (items within each menu) is displayed on the fingers of the dominant hand (© 2001 IEEE).

encompassing aspects like emotions, physiological data, and overall well-being. As noted by Gutwin and Greenberg in 2002, conventional groupware systems often fall short in presenting the limited perceptual information available to them, highlighting a crucial gap in fostering awareness within digital workspaces [64].

From this perspective, two primary research directions emerge: enhancing the generation of perceptual information and improving the presentation of existing data. While current literature proposes various techniques for both endeavours, there remains potential for further advancements in improving awareness. In this context, this dissertation focuses on the latter research direction, exploring optimal strategies for sharing information about team members with their peers or leaders. Additionally, it delves into the identification of key information indicators that significantly enhance team performance when assigning tasks to a group of workers. By investigating the potential benefits of sharing already available information among collaborators and identifying the most relevant indicators for different scenarios, this research aims to enhance collaboration efficiency without overwhelming users with excessive information. Through these efforts, this dissertation strives to contribute to the ongoing discourse on collaborative awareness, with a focus on practical efficiency rather than exhaustive exploration.

IMPROVING SYNCHRONOUS COLLABORATION BY SHARING USERS' STATUS

This chapter will address **RQ1 – How does sharing users' status with XR improve collaboration?** First, with **RQ1.1 - How can a shared workspace and its users be augmented to improve collaboration?**, and after narrowing down the potential options, the focus will be on perceiving how well collaborators cope with their work. Before even having a precise idea of the well-being of collaborators, it is important to know if this awareness could increase mutual help in teams, hence the second and third research questions arise: **RQ1.2 - Does sharing user status enhance the detection and characterization of a need for help?** and **RQ1.3 - Which user status data are the most useful to detect and characterize a need for help?**

Indeed, in many real world scenarios, people need to work together, being collocated or distant. Collaborative Virtual Environments (CVE) tend to reduce the distance between collaborators by using Virtual Reality (VR) or Augmented Reality (AR) to create shared workspaces. While VR and AR have been studied since the middle of the 20th century, Computer Supported Collaborative Work using immersive technologies (XR-CSCW) continues to face significant challenges [135]. At the same time, empathic computing aims to create a deeper shared understanding between people [113]. Whilst there are applications of CVE in many domains, such as education and training [79], entertainment and gaming [145], manufacturing [17], architecture [110], and engineering [18], there is still a lack in the perception of other users activity and emotional states [15], so these perceptions need to be studied.

As presented in the previous chapter, the awareness of collaboration is based on workspace awareness [16, 64, 86] (sum of knowledge, perception, and understanding of an environment) and empathic computing [114] (how technologies can be used to help

increase empathy or create deeper shared understanding between users). These studies aim to investigate how individuals' experiences influence their emotions and metabolic processes. Therefore, consideration is given to exploring the concept of user status based on awareness components for the dual purpose of recognizing individuals and characterizing their actions and internal conditions, including factors like physiology, emotions, and cognitive workload, among others.

The contributions presented in this chapter aim to enhance teamwork, focusing on worker well-being, task completion efficiency, and team adaptability. These contributions include visualization techniques designed to display collaborators' status indicators attached to workers' wrists, conceptualized to monitor whether any team member requires assistance. To facilitate the study of these concepts, a collaborative system has been developed, and the visualizations have been implemented as indicators specifically tailored to this system. While the system-specific indicators are utilized in a user study, it is important to note that the concepts themselves are being evaluated and can be applied to a wide range of collaborative systems.

The first section relates the main contribution of the chapter: the investigations for methods to enhance the awareness of collaboration in virtual environments by providing user status and activity indicators, facilitating the detection of when assistance is needed. Several visualization techniques were initially proposed to convey the activity and task status of multiple users. The second section of this chapter presents the experimental platform, a virtual reality adaptation of the NASA MATB-II (Multi-Attribute Task Battery), developed to evaluate the scientific propositions made throughout the dissertation. One of the visualization techniques was selected for a pilot study, and its benefits were evaluated in a controlled experiment, presented in the last section of the chapter.

3.1 Visualizing user status

This section presents a series of visualization techniques designed to convey user status across four distinct categories: collaborators' identification, activity, physiological metrics, and indirect measures (computed from both activity and physiological data). Within each category, various indicators are proposed based on the task and collaborative contexts. These visualization techniques serve the purpose of furnishing users with information about a collaborator's activity, facilitating the detection of assistance needs without imposing a significant mental workload on the observer. As presented in Section 2.4, two key

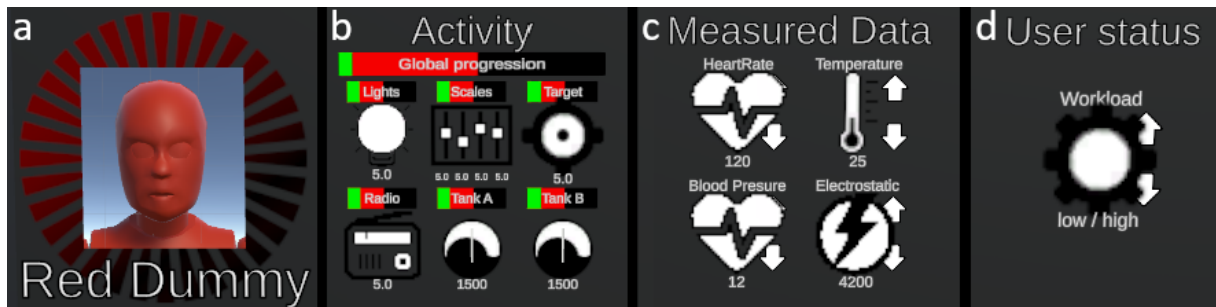


Figure 3.1 – User status indicators divided into four groups: (a) identification, (b) task status, (c) physiological measures, and (d) indirect measure of user status.

design dimensions were considered for information display: (i) symbolism and (ii) placement. In terms of symbolism, a hybrid strategy was adopted, integrating symbolic representations with literal values. The initial segment of this section presents the proposed indicators. The subsequent segment explores diverse placements for this panel within the workspace.

3.1.1 Indicators

Sharing information about a user's activity/status is an effective method to enhance collaborative awareness. During a collaborative task, it is mandatory to share elements answering the *Who / What / Where / How / When* questions to improve understanding among users [64]. A 2D panel gathers all indicators representing the user status (see Figure 3.1). These indicators are divided into four groups: (a) identification, (b) task status, (c) physiological status and (d) indirect measures of user status.

The identification panel (a) offers three ways to bind the status data to someone in the workspace, building awareness elements answering to the *Who* question. Each collaborator is attributed three unique identifiers, a colour (displayed as a background disc), a textual name (written at the bottom of the frame) and a visual (with a picture in the centre of the frame). A full-body avatar creates visual and spatial awareness elements for the *Who* and *Where* questions and situates a user in the workspace.

To give information for the *What, How* and *When* questions, the tasks status panel (b) regroups two kinds of indicators: progress bars and icons. Progress bars are designed to give progression information on a task and the icons are designed to give information about the current state of a task. During collaborative work, each user can be charged with tasks which will create a task load. Each task can be rewarded with a score, contributing

to the final cumulative score of a global activity. The progress bars show in red the sum of the task load from the beginning of the activity and in green the cumulative score. With a perfect score, i.e. a perfect completion of the task, the green bar would fully hide the red bar. A global progress bar shows the sum of all task load scores. At the end of an activity, red bars will fill the black background. The icons refer to a task or a part of a task, white icons fade to red as their bounded task triggers and time passes. When a task is inactive, its icons are coloured in white. When a task reaches its time limit, the coloured part(s) of the icon is(are) red if the task is still not properly achieved. These concepts can be applied to a wide range of collaborative tasks, only their implementation varies depending on the applicative context.

The other indicators mainly address the *Who* and *How* questions with both direct and indirect measures. These are completed with the physiological status panel (c), a mock-up of how physiological data could be presented. Icons referring to heart rate, skin temperature, blood pressure and skin electrostatic conductivity are used to illustrate the mock-up. Each icon would refer to a physiological measure, the white colour could be replaced by green to show “good” values and by red to show alarming values. As the variation of this kind of measure can be more important to perceive than the actual value, arrows can be displayed and hidden depending on whether the value varies or not.

The indirect data panel (d) shows computed measures of user status, as well as a mock-up. Cognitive workload, whether estimated by a machine learning algorithm from physiological data or self-reported, serves as a more reliable indicator of individuals’ well-being than task performance alone [92]. This suggests that regardless of the measurement method employed, cognitive workload provides valuable insights into an individual’s state.

3.1.2 Placement

The search for the optimal information placement within a user-shared workspace is imperative. This section explores two primary approaches: (i) distribution and (ii) aggregation of information.

With a distributive placement, each piece of information is situated close to the person or object it refers to (see Figure 3.2.a). Early pilot experiments showed that placing information panels on top of the head of a close collaborator avatar was irrelevant, people would not raise their head to look at the panel. Pilot experiments showed that people were not looking at fixed panels (either as a workspace prop or as a panel attached on top of their collaborators) and that the movable artifact was not convenient because it needed

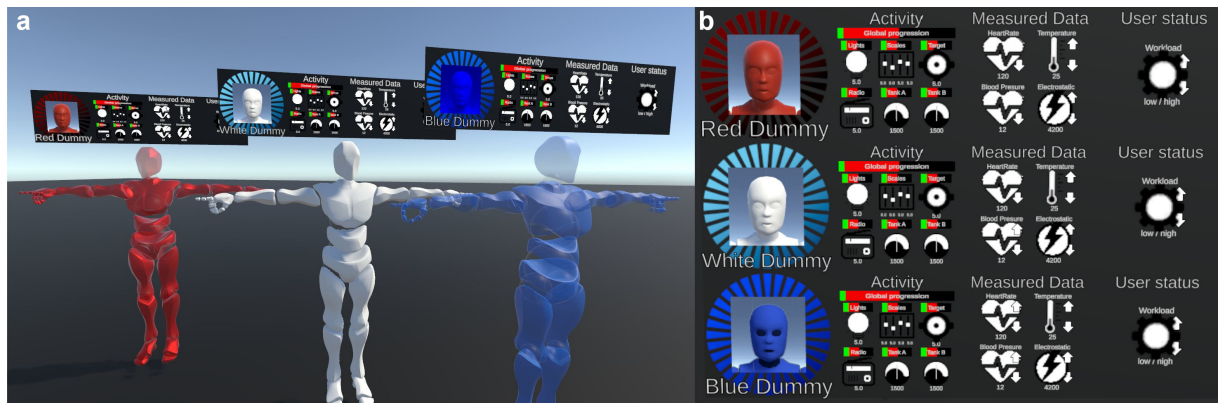


Figure 3.2 – Workspace situated placement: (a) distributive placement - each panel is attached relative to the user it refers to; (b) aggregative placement - all information is gathered on the same panel.

one hand to be moved. A design decision was made to have an aggregative placement, with all information gathered in the same place. An aggregative panel (see Figure 3.2.b) can take multiple forms: a fixed panel in the workspace (see Figure 3.3), a movable artifact (see Figure 3.4), or a body relative (see Figure 3.5).

3.2 Experimental platform: a generic way to address work with MATB-II

Given the visualizations of user status proposed in the previous section, an evaluation required a system that would place users under pressure, leading them to seek and provide assistance at some point. The context chosen for this is the NASA MATB-II (Multi-Attribute Task Battery) [129], mainly used to assess mental workload, as it is designed to put the user in a stressful context creating a mental workload with the simultaneous performance of multiple tasks. This system has been used to design training scenarios [92], to study relations between cognitive control modes and mental workload [123] and for real-time estimation of the mental workload with machine learning [92]. This section presents the VR adaptation of MATB-II created for experimental purposes while the original system is presented in an appendix "MATB-II original design".



Figure 3.3 – Aggregative: Panel, the information is in a fixed place in the workspace.

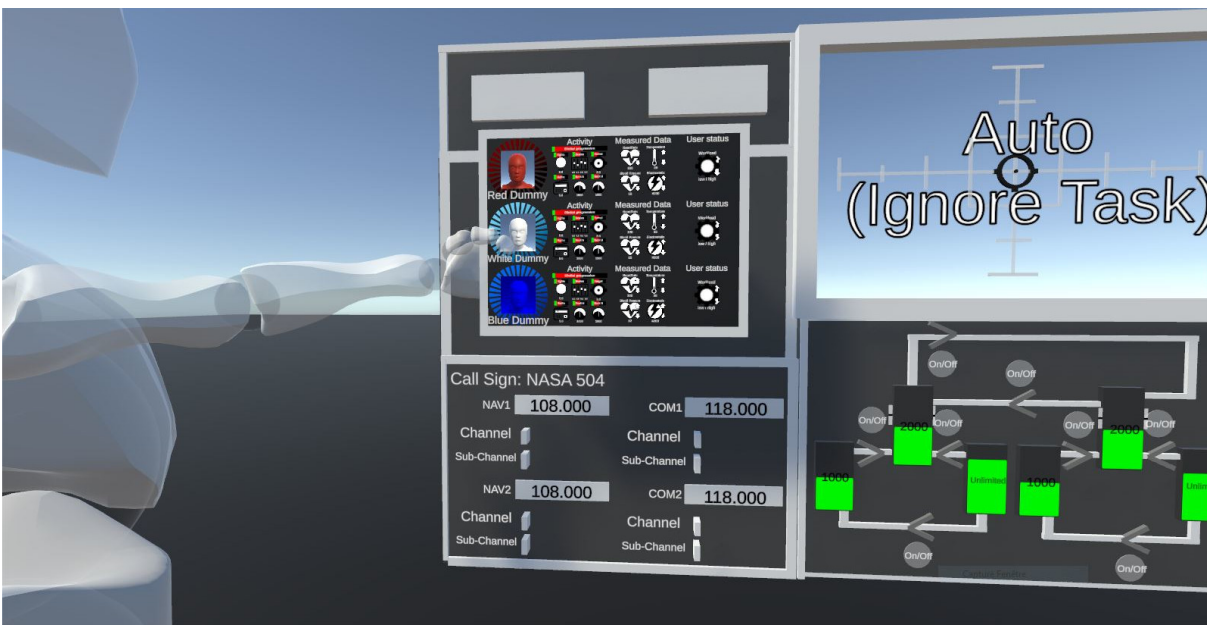


Figure 3.4 – Aggregative: Tablet, the information is brought together in a manipulable object.

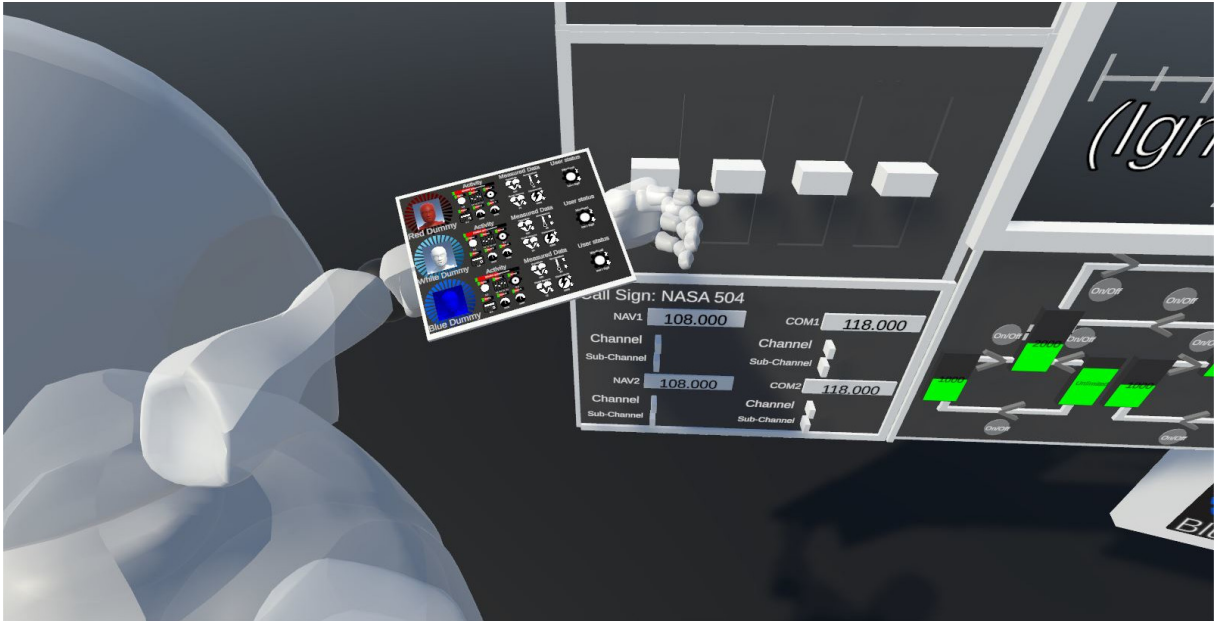


Figure 3.5 – Aggregative: Body relative, the information is displayed on the avatar forearm.

3.2.1 Implementation of the visualizations

The indicators presented in Section 3.1.1 were implemented to display the status of the MATB-II tasks, as depicted in Figure 3.6. Each indicator provides feedback on a specific task:

- (a) The *Lights* indicator monitors the SYSMON task. When the SYSMON lights deviate from their normal state (either *on* or *off*), a red progress bar fills against a black background. Simultaneously, a green progress bar appears, indicating the score attained from the task (reflecting the speed at which the lights return to their normal state). If any of the SYSMON lights are not in their normal state, the light bulb icon gradually transitions to red until task failure.
- (b) The *Scales* indicator tracks the SYSMON task. As the SYSMON scales deviate from the centre of the panel, a red progress bar fills against a black background. Similar to the *Lights* indicator, a green progress bar reflects the task score, and any deviation prompts the associated square to transition to red until task failure.
- (c) The *Target* indicator provides feedback on the TRACK task. When the TRACK task triggers and the target moves away from the centre of the frame, a red progress bar fills against a black background. The green progress bar indicates the task score



Figure 3.6 – Status of MATB-II tasks: SYSMON (a,b), TRACK (c), COMM (d), and RESMAN(e,f).

- (reflecting the duration the target remains centred). The TRACK icon reflects how far the target is from the centre of the frame gradually fading to red.
- (d) The *Radio* indicator provides feedback on the COMM task. As the COMM task initiates and an audio message is played, a red progress bar fills against a black background. The green progress bar reflects the task score (indicating speed and accuracy). During task execution, the radio icon gradually fades to red until task failure.
- (e,f) The *Tank* indicator monitors the RESMAN task, with separate indicators for tanks A and B. A red progress bar fills over time against a black background, with a green progress bar indicating the task score (reflecting how long the tanks remain in the optimal range). While within the optimal range, the gauge icon remains white; deviation prompts the associated gauge icon to fade to red, indicating the distance from the optimal range.

3.2.2 MATB-II adapted to XR

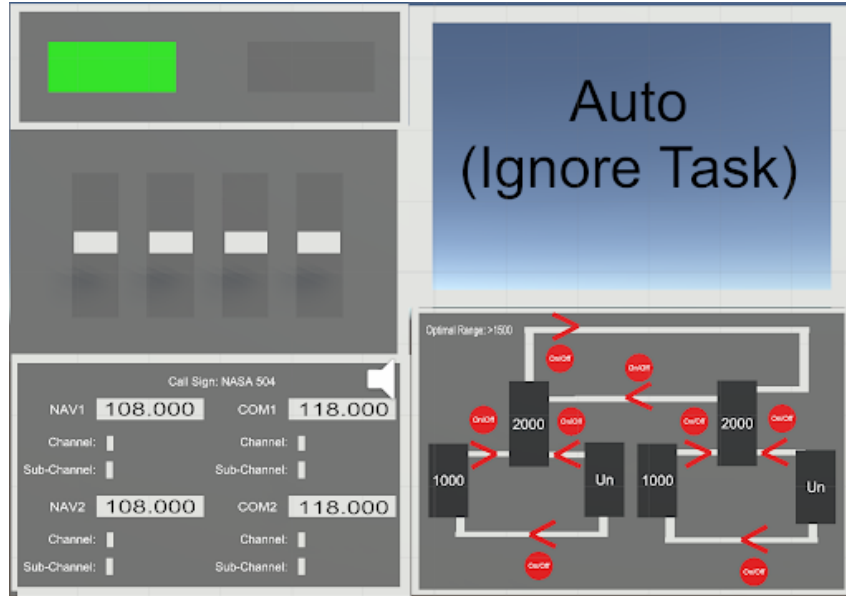


Figure 3.7 – Implementation of the MATB-II system in virtual reality.

The XR collaborative platform used in works presented throughout this dissertation to experiment and evaluate research propositions is an XR adaptation of MATB-II¹. This tool was extended to create a collaborative environment where users would cooperate to complete tasks as fast and as accurately as possible. While S. Singh et al. chose a dynamic split of task responsibilities between a single human and AI when transforming the MATB-II into a collaborative application [138], the approach presented here enables interaction among multiple humans. The MATB-II-CVE application (see Figure 3.7), was developed using Unity 2018², C# scripts³, the SteamVR framework⁴ for VR tracking, and Photon⁵ to handle the network code. To study the awareness of collaboration, the MATB-II-CVE application split the responsibility of four tasks between two human users: the participants

1. Initial Unity project including a base interface and system was provided by Jamie Gower, PhD student at UniSA.

2. Unity 2018: Game Engine allowing easy and moduable Entity Component System (ECS) development.<https://unity.com/>

3. C#: High-level programming language created by Microsoft, used as a scripting language in most Unity projects.<https://learn.microsoft.com/en-us/dotnet/csharp/>

4. SteamVR: VR framework created by Valve, tools to help developers to create VR applications.<https://www.steamvr.com/>

5. Photon: Network framework created by Exit Games, tools to help developers create network applications.<https://www.photonengine.com/>

would have the COMM and RESMAN tasks, the confederate/experimenter the SYSMON and TRACK tasks, both users having one monitoring task and one activated task. Two of the six tasks of the original design have been dropped: the SCHED and the WRS. Indeed, the scheduling task has been removed to make detecting the need for the help of a collaborator more difficult. The workload rating scale was breaking the continuous collaboration, thus it was replaced by a questionnaire at the end of the session. The sources of the Unity Project and compiled versions of the application can be used by anyone who would want to study collaboration in an environment that can put pressure on users, available at: https://github.com/ThomasRinnert/MATB-II_CollabVR.

3.2.3 Pilot experiments

Pilot experiments were run alongside the development of the visualization techniques and the experimental platform. The results of these experiments were purely qualitative and only helped to design the indicators and the collaborative XR application for the study. Quickly, pilot experiments showed that placing information panels on top of the head of a close collaborator avatar was irrelevant, as people would not raise their heads to look at the panel. With more distance between users or a different presentation of information (e.g. augmented avatars), the distributive placement would be more useful. However, large distances were not evaluated in the pilots, as a requirement of the experimental platform was to allow users to move inside the workspace without any special navigation technique other than real movements. Pilot experiments also showed that people were not looking at fixed panels either and that the movable artifact was not convenient because it needed one hand to be moved, thus the body-relative placement was selected to evaluate the visualisation propositions.

In the early development of the application, users were side by side facing a unique MATB-II interface (see Figure 3.8). It was observed that obtaining adequate information about task status merely required a small step back or a slight turn of the head. Notably, any additional indicators did not contribute to improved collaboration. Two alternatives were considered to address this observation: doubling the number of MATB-II systems with one complete interface per system, or subdividing the tasks of a single MATB-II system across distinct panels. The latter option was selected to maintain experimental simplicity, resulting in the division of the interface into two panels positioned facing each other (see Figure 3.9). This arrangement was designed to increase the difficulty of acquiring task status information. Additional arrangements were envisioned but not explored, see

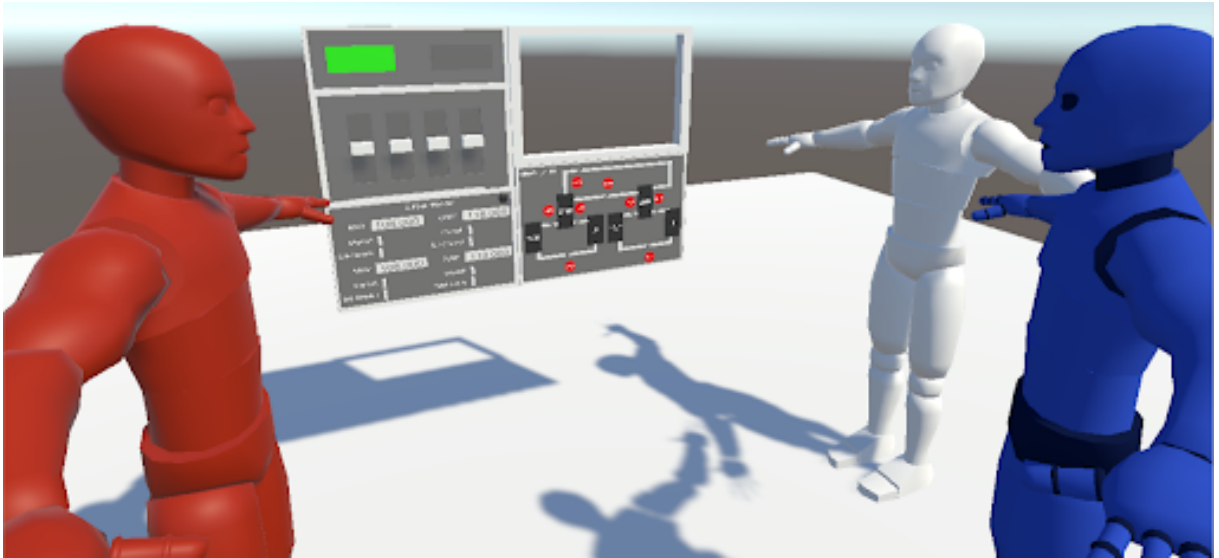


Figure 3.8 – Scene arrangement setting all users facing a single MATB-II interface.

appendix "MATB-II-CVE unexplored configurations".

During the parameter refinement phase of the experiment's preparation, it was observed that allocating dynamic responsibility for tasks resulted in prolonged experiment durations and blurred the notion of assistance between users. Furthermore, this phase revealed that participants consistently had sufficient time to assist a confederate who simulated needing help. The investigation determined that a duration of 10 minutes was sufficient; indeed, the confederate required assistance on 10 occasions within that time-frame (comprising 6 SYSMON tasks lasting 10 seconds each and 4 TRACK tasks lasting 30 seconds each).

3.3 User study: sharing users' activity during XR synchronous cooperation

K. Schmidt [133, 134] classified cooperation into three categories: (i) augmentative cooperation, where everyone has the same interaction capabilities; (ii) integrative cooperation, where people have complementary interaction capabilities; and (iii) debative cooperation, where discussion and strategy are the main parts of the collaborative activity.

Dynamic distribution of the roles (debative cooperation) was avoided to ensure quantifiable mutual assistance, minimizing the occurrence of false positives arising from task

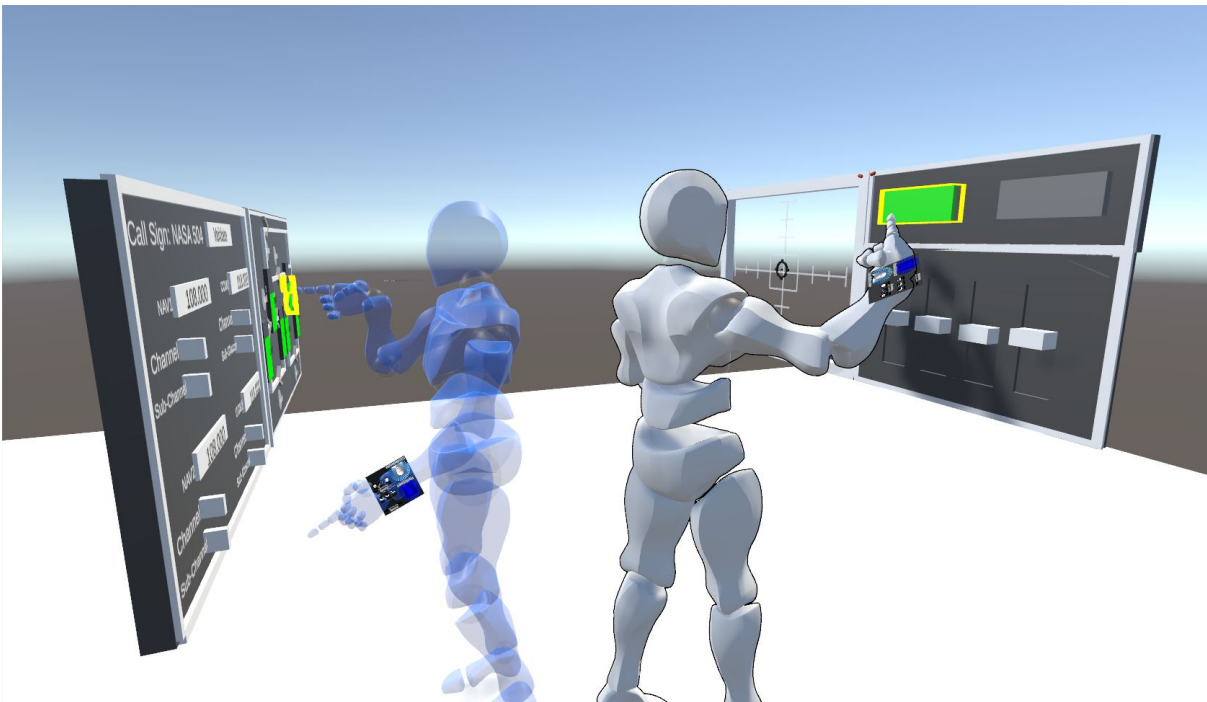


Figure 3.9 – MATB-II system cut in two halves facing each other. The confederate’s avatar is on the left in front of the first half of the interface with the TRACK and SYSMON tasks, and the participant avatar is on the right in front of the other half of the interface with the COMM and RESMAN tasks.

reallocation. When adapting MATB-II to XR, two options remained: either users would have needed their partner to complete each of their tasks (integrative cooperation), or users could complete all the tasks on their own except when they were overloaded, and only then would one's partner help by doing one's task for one (augmentative cooperation). Participants would collaborate with an experimenter (confederate) on the MATB-II with the participant having full responsibility for the COMM and RESMAN tasks, and the confederate having the responsibility for the SYSMON and TRACK tasks.

Opting for augmentative cooperation helped to have an invariant need for help in task scenarios: to simulate a need for help, the confederate abandoned their tasks regularly (1/2 of the TRACK tasks and 1/3 of the SYSMON tasks), at the same time for each participant, waiting for them to help. The confederate was well-trained on the MATB-II and fulfilled their role quickly and accurately.

This section reports this controlled 1×2 within-participant study (approved by the ethics committee of IMT Atlantique on 2 December 2021, approval ID: 012021) was conducted on the experimental platform to evaluate how relevant the indicators are for representing the user's activity. In these experiments, only two of the four proposed panels are implemented: the identification and activity status ones. Two conditions were evaluated, with and without user activity sharing respectively labelled as *AggData* and *NoData*.

3.3.1 Participants

The user study was conducted from the second half of December 2021 to the end of January 2022 at IMT Atlantique, Brest campus, France. Twenty unpaid volunteers (7 females, 13 males) aged from 18 to 65 years old (mean: 26.7, sd: 10.7) were recruited and asked to rate on a scale from 0 to 4 their use of video games (mean: 2.3, sd: 1.5), 3D environments (mean: 2.15, sd: 1.6), and immersive technologies (mean: 1.55, sd: 1.4).

3.3.2 Apparatus

For the experiment, two unobstructed floor spaces of at least 2×2 meters, two VR-ready computers (DELL laptops, DELL, Round Rock, TX, USA, i7-10850H, 32GB RAM, NVIDIA Quadro RTX 3000) connected either via the Internet or a Local Area Network (respectively cloud or self-hosted Photon server), two immersive Head Mounted Displays (HMD) – a HTC Vive Cosmos for the confederate & an Oculus Quest 2 for the participants – and their controllers were required. The immersive technology difference did not affect

the user experience, as both HMDs offered the same interaction capabilities and the same feedback from the virtual environment. Furthermore, all the participants used the same Oculus Quest 2, and the confederate always used the same HTC Vive Cosmos. This did not induce variability in the experiment, so it did not affect the results. The collaborative virtual environment used for this study was the MATB-II-CVE, the participant and the confederate interacted with the split MATB-II.

3.3.3 Data Collection

In this study, there was only one independent variable: the data presentation mode. This factor has two possible values in this context: no data presentation (*NoData*) and an aggregative body-relative presentation (*AggData*) (see Figure 3.5). The dependent variables can be categorized into two groups: objective measures (all quantitative) and subjective measures coming from questionnaires (available in the appendices).

- Objective measures:
 - Reaction Time – time between activation of a task and the first interaction of a participant with this task;
 - Completion Time – time between the first interaction of a participant with a task and its completion;
 - Success rate – each task resolves with a success or a failure;
 - Score – value addressed to a task depending on the speed of its completion and the precision of the user response;
 - Expected Help – number of times the participant helps the confederate when expected;
 - Unnecessary Help – number of times the participant helps the confederate when there is no need.
- Subjective measures:
 - Demographics – age, gender, and video games / 3D environments / immersive technology habits (on 5-level Likert scales, from "not at all" to "expert");
 - Evaluation of the progress bars (usage and quality, on 5-level Likert scales);
 - Evaluation of the icons (usage and quality, on 5-level Likert scales);
 - Estimation of participant's self-ability to detect that the confederate needs help with and without indicators (yes/no questions);
 - Estimation of participant's self ability to help the confederate needing help (yes/no questions).

3.3.4 Protocol

First, the participants are given detailed information and explanations, see the "XP1 - Information sheet for participants" and "MATB-II-VR User guide" as appendices at the end of the manuscript. Then, after signing the informed consent form, also available as an appendix, participants were equipped with an immersive head mounted display (HMD) and its controllers and started the initial training phase. For each condition, participants went through an additional training phase and a ten-minute task scenario, collaborating with the confederate. At the end of the experiment, participants were asked to answer a questionnaire to gather demographic data and subjective evaluation of the proposed indicators, see "XP1 - End of experiment questionnaire" as an appendix at the end of the manuscript. The experiment lasted forty-five minutes for each participant.

There were three training phases: the initial training phase and two condition training phases. During the initial training, the participant could experience the completion of each task one after another: once the RESMAN, the training stopped when the participant clearly said that they understood the functioning of all the pumps; the SYSMON task twice; the TRACK task once; the COMM task twice; all messages not addressed to NASA-504 were ignored in the count. The participant could ask to retry as many tasks as they wanted until ready to begin a 10-minute scenario. Before each condition, the tasks triggered once each, one after another in the same order as the initial training phase. For the *NoData* condition, the participants were asked to complete the task as they triggered, this was followed by the simultaneous activation of all tasks at once where the participant and the confederate completed their task together. For the *AggData* condition, the participants were asked to watch the indicators as the task went on while the confederate gave a detailed explanation of them. This was followed by the simultaneous activation of all tasks at once where the participant and the confederate completed their task together.

Throughout the experiment, both the participant and the confederate had to complete two scenarios on the MATB-II interface, each lasting 10 minutes. The determination of this duration was based on preliminary pilot experiments investigating participant assistance to the confederate. Indeed, within this 10-minute timeframe, the confederate required assistance on 10 occasions, comprising 6 SYSMON tasks lasting 10 seconds each and 4 TRACK tasks lasting 30 seconds each. This duration proved sufficient to gauge whether the participant offered assistance to the confederate. Each scenario, with a fixed set of tasks (12 COMM, 12 TRACK, 12 RESMAN, and 18 SYSMON), aimed to impose a workload on the users by activating multiple overlapping MATB-II tasks, necessitating simultaneous

work by both the confederate and the participant. The fixed duration of 10 minutes was deemed adequate for measuring participant assistance to the confederate. A scenario contained a fixed number of tasks (12 COMM, 12 TRACK, 12 RESMAN, and 18 SYSMON) to create a workload for the users, and activated multiple MATB-II tasks that overlapped in time, so the confederate and the participant had to work at the same time. It was divided into 3 phases, “*participant is loaded more than confederate*” at the beginning and the other two phases were interchangeable, “*confederate is loaded more than participant*” and “*both users are loaded*”. Verbal communication (apart from reporting an issue) was prohibited to simulate distant collaboration in a noisy workspace. The confederate simulated a need for help by not doing a task following an invariant predefined scheme (1/2 of the TRACK tasks and 1/3 of the SYSMON tasks).

3.3.5 Hypothesis

The following hypotheses were formulated about the users’ task status indicators:

- H1 *AggData* would improve overall task performance compared to *NoData*. The performance is measured by four values: the score, the success rate, the reaction time and the completion time of the tasks.
- H2 *AggData* would improve mutual support compared to *NoData*. This is measured by counting the number of times participants will help the confederate (Help measure), also this could be correlated with the results from the questionnaire about self estimation of help efficiency.
- H3 People would prefer instantaneous information conveyed by icons to a history constructed from the progression bars in terms of activity feedback. This could only be measured by data gathered via the questionnaire.
- H4 People would more easily detect that a collaborator needs help with *AggData* compared to *NoData*. Again, this could only be measured by data gathered via the questionnaire.

3.3.6 Results

In this study, the presentation of data follows a structured approach, commencing with the exposition of objective and parametric data, succeeded by subjective and non-parametric data. Each participant underwent two conditions, generating a total of 40 data points ($2 \times 20 = 40$). The normality of the parametric data distribution was assessed

through Shapiro-Wilk tests, revealing a non-normal distribution in all cases. Consequently, Wilcoxon signed-rank tests were employed to check for a significant effect of the Aggregative board on both parametric and non-parametric data. When reporting results, the means will be presented followed by the standard deviation and the test statistics.

The results were analysed with Python libraries, the most relevant being *pandas*, *SciPy* and *statsmodels* with *Matplotlib* to generate the plots.

Objective data

No significant difference between the two conditions for the objective data could be observed, a summary of the data analysis can be found in Table 3.1.

measure	<i>NoData</i>	<i>AggData</i>	p
reaction time (s)	8.82 ± 4.0	8.60 ± 3.4	0.65
completion time (s)	3.24 ± 1.8	3.57 ± 1.6	0.60
score [0-1]	0.821 ± 0.11	0.830 ± 0.080	0.74
success rate [0-1]	0.840 ± 0.13	0.859 ± 0.095	0.37
expected help	85 ± 20	87 ± 10	0.90
unnecessary help	13 ± 15	18 ± 19	0.47

Table 3.1 – Objective data analysis summary.

Subjective data

Concerning subjective data, participants evaluated bars and icons on two aspects: frequency of use and a score, both on a [0-4] scale. The frequencies of use of the bars and icons were significantly different (*bars* = 1.55 ± 1.23, *icons* = 2.80 ± 1.15, $W = 13.5$, $p = 0.004$, $r = -0.640$). The scores attributed to the bars and icons were significantly different (*bars* = 1.80 ± 1.28, *icons* = 2.75 ± 1.12, $W = 26.0$, $p = 0.007$, $r = -0.600$). The icons were more used and preferred to the bars (Figure 3.10). Participants also evaluated their ability to detect that their collaborator needs help and their ability to help a collaborator needing help with the two conditions, all with a binary response (*No* or *Yes*). Participants' perception of their ability to detect the need for help with *NoData* and *AggData* was significantly different (*NoData: ability* = 0.35 ± 0.5; *AggData: ability* = 0.65 ± 0.5; $W = 4.5$, $p = 0.034$, $r = -0.47434$). However, the difference in participants' perception of their ability to help with *NoData* and *AggData* was not significant (*NoData: ability* = 0.60 ± 0.5; *AggData: ability* = 0.75 ± 0.4; $W = 0$, $p = 0.083$, $r = -0.3873$). Although the estimation

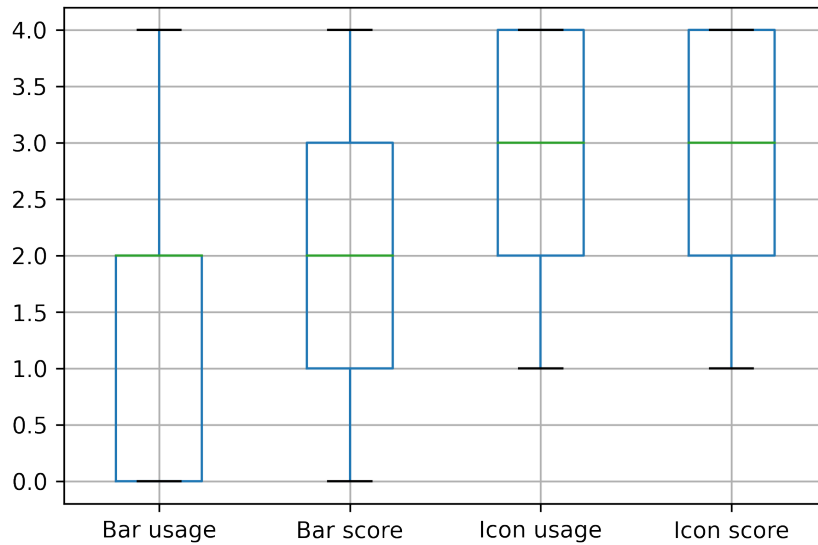


Figure 3.10 – Evaluation of bars and icons in terms of usage and score.

of their ability to help the collaborator is not significantly improved, the addition of indicators allows users to estimate they better detect a collaborator’s need for help (see Figure 3.11).

3.3.7 Discussion

Objective measures cannot support **H1**, since reaction time, completion time, score or success rate were not enhanced by the *AggData* condition. **H2** cannot be supported either, whether using objective measurement of expected and unnecessary help counting or subjective data from the end-of-experiment questionnaire on self-estimation of ability to help a collaborator. For both of these hypotheses, it seemed relatively straightforward to identify when the confederate required assistance as they ceased activity on the MATB-II system. Participants could effortlessly check for a need for help with a glance and thus ensure a good performance regardless of the conditions. A plausible explanation for this behaviour is that participants harboured concerns about their ability to assist the confederate in the *NoData* condition. Consequently, participants vigilantly monitored the confederate’s need for help every few seconds, potentially compromising their own task performance. This could explain why the experiment failed to demonstrate with quantitative measures the benefits of sharing the user status. **H1** and **H2** are not validated but at least, the interaction does not suffer from employing user status panels: sharing

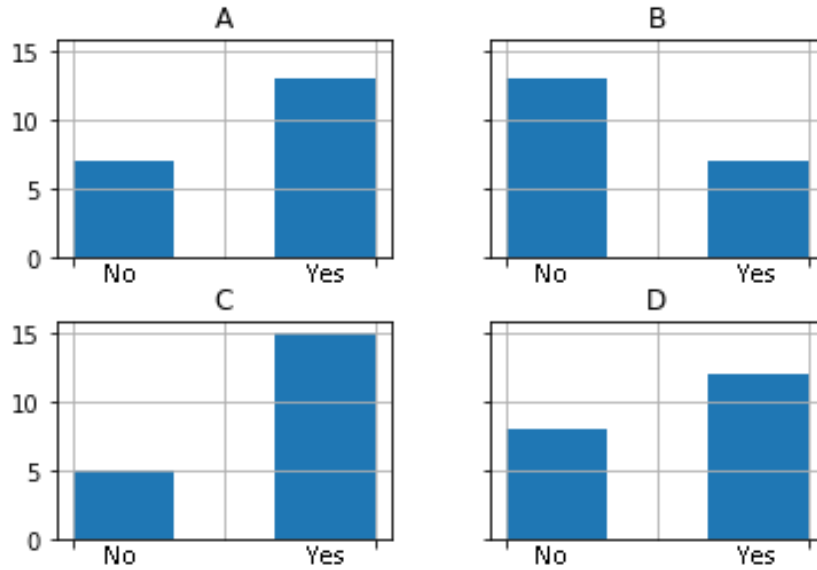


Figure 3.11 – Evaluation of self-ability to help a collaborator: evaluation of self-ability to detect that a collaborator needs help with *AggData* (**A**) or with *NoData* (**B**); evaluation of self-ability to help a collaborator with *AggData* (**C**) or with *NoData* (**D**).

such information can be further explored to study the awareness of collaboration and how to enhance collaborative awareness.

Results from the questionnaire show that icons were used significantly more often and preferred by participants compared to progress bars for monitoring the collaborator's activity in the context of continuous interaction with the MATB-II system. This supports **H3** and demonstrates that users rely more on instantaneous activity feedback than a history of progression for such continuous collaboration with symmetrical interaction capabilities among collaborators. Although the estimation of self-ability to help the collaborator is not significantly improved, the user status indicators significantly allow users to estimate they detect a collaborator's need for help with more ease, which supports **H4**.

This experiment was a generic way to assess real use cases of teamwork. Sharing users' activity to improve teamwork can be applied to different situations: command centres [120], airliner pilots [13], air traffic control [94, 104, 149], or any other type of augmentative computer-supported collaborative work (CSCW) between humans.

The main limitation of our experiment is that it focuses only on a specific type of collaborative task. Given that MATB-II is a realistic simulation of a stressful situation, it enables us to place a task load on users [129]; however, it was not originally designed

to be collaborative. Only augmentative cooperation can be done on a single MATB-II: users having the same interaction capability prevent integrative cooperation, and when a scenario is launched, the team has no time for debative cooperation. In this context, the sole means of assisting was by completing the task on behalf of someone else. Such intervention proved to be unpleasant, as it involved interference with one's task and potential judgment regarding the perceived quality or speed of the work. This could explain why the experiment failed to demonstrate with quantitative measures the benefits of sharing the user's activity. To draw a more generic conclusion about collaboration in VR, it would be necessary to also address all the categories of collaborative tasks.

3.4 Conclusion

Efficient collaboration in VR requires not only perceiving partners' positions and actions but also understanding their status (task activity, emotional states, fatigue, etc.). Several solutions were explored to visualize and share the user's activity/status in a collaborative virtual environment. Although it was not demonstrated that sharing user task status would enhance task performance or help occurrence, giving information about the task status enhances the detection of the need for help. Furthermore, people prefer instantaneous information to a progression history in a continuous augmentative cooperation scenario, this must be considered when designing task status feedback for this mode of cooperation.

Investigating the distribution of tasks and the balancing of the workload of a team would create the opportunity to explore the integrative cooperation mode. The next two chapters will present work on providing team members' status feedback to their leader to improve team performance.

IMPROVING TEAM MANAGEMENT BY SHARING COLLABORATOR'S STATUS

The previous chapter showed that giving information about collaborators' task status enhances the detection of the need for help. Beyond easing the detection and characterisation of individuals' need for help, sharing the status of workers can potentially enhance a team leader's ability to better allocate tasks to their team, improving both performance and the team members' well-being. Real-time and high-intensity teamwork management is complex, as team leaders must ensure good results while also considering the well-being of team members. Given that stress and other factors directly impact team members' output volume and error rate, these team leaders must be aware of and manage team stress levels in combination with allocating new work. This chapter examines methods for visualizing each team member's status in extended reality, which, combined with a simulated stress model for virtual team members, allows the team leader to consider team members' statuses when choosing who to allocate work. Given one of the roles of a team leader is to accomplish work through other people [72], the visualisations presented in the chapter aim to minimise the time it takes and improve the information for a leader to make decisions that optimise the whole team's performance and the empathic health of the team members.

For team leaders to maximize the effectiveness and efficiency of their team as individuals and as a whole, they need to understand the current empathic state [114] of their team members. For these leaders, workspace awareness defines the knowledge required for workers to interact with a system, utilizing the up-to-the-moment understanding of other people's actions [135]. While team leaders can obtain feedback on their team performance and status through 2D interfaces, AR presents in-situ information related to team members in the physical space [159]. This information could be represented in various ways, e.g. literal versus symbolic [64, 135], and could even include state information, for example, whether the team member is browsing information or performing focused

work on it [77]. However, actively communicating this information can be complex, given the team constitutes many individuals. Additionally, each team member has to manage their own tasks, workload, and stress levels, which team leaders must be aware of and actively monitor. Previous work has examined the effects of sharing physiological states in collaborative VR (e.g. heart rate [36, 37]), as well as the development of collaborative awareness by using realistic avatars [12, 161], sharing gaze [9, 52, 118], and even emotions [109]. Understanding a team member’s direct and passive actions and behaviours provides team leaders with a much broader range of information when making decisions that impact a team member [75]. This work explores the development of AR visual cues to help team leaders understand the state of their working team members when allocating new tasks to them, as explored by Lee et al. where a local worker shares visual cues with a remote helper [89]. This allows the team leader to individually manage the workload and well-being of individual members while maximizing task outputs for the team overall.

In this chapter, the focus turns to address the second research question: **RQ2 – What are the elements helping leaders to understand their team members’ status and how to present them?** Consequently, this dissertation will explore **RQ2.1 - Does providing information about a team member’s stress status and current workload help team leaders manage a team?** and **RQ2.2 - Which AR visualizations are most effective in helping team leaders understand the status of their team members?** The former aims to identify the most critical measures for a team leader to consider, and the latter delves into the investigation of how such information should be presented.

Different AR presentation methods of status information to a team leader were developed, communicating individual team member’s status. The goal is not to investigate methods of physiological sensing or human tracking technologies but to determine the effectiveness of different visual attributes of AR presentations. This is why simulated team members are employed for research purposes, as the focus is on the effect of sharing the team members’ status and not on how to gather it. The AR information is simulated in a VR environment, and the simulated team members are placed in that VR setting. The simulated team members’ well-being is presented to the team leader labelled as stress¹, following Lazarus and Folkman’s definition as "a particular relationship between the person and the environment that is appraised by the person as taxing or exceeding his or

1. Stress is an extremely complex concept and topic. The use of this term in this dissertation is meant to provide a high-level term covering a person who is experiencing such emotions as being overworked, unable to finish tasks on time, pressured, and falling behind on their work.

her resources and endangering his or her well-being" [83]. This investigation focuses on improving information presented to the team leaders who are required to know who is over or under-loaded and how they are coping with that work. The presentation of this information aims to allow the team leader to balance between having the work done and maintaining a healthy and efficient working environment. The usage of virtual workers in this experiment enables the investigation of the impact of providing feedback on their workload, individual performance, and inner status on overall team performance. However, it is essential to note that before deploying such visualizations in a team of real people, obtaining explicit consent from team members for sharing their personal data would be mandatory. This process would not be imposed on them but conducted with their informed consent. Importantly, any use of such data should be solely dedicated to improving their well-being at work and must not, under any circumstances, be a tool to exploit people for their ultimate resources. Future research will investigate the ethical and privacy concerns with AR-presented information in a physical setting with human team members and physiological sensing.

The first section of this chapter details the design of status visualization techniques, categorized into two distinct groups: task status for workload-related information and inner status for monitoring the well-being of individuals. The second section presents the experimental platform, where a user has to assign work to virtual workers operating the virtual reality adaptation of the NASA MATB-II (Multi-Attribute Task Battery) presented in the previous chapter. Those techniques were evaluated in a controlled experiment, presented in the last section of the chapter. The results showed that (1) providing AR feedback on team members' internal status increases the team's overall performance, as team leaders can better allocate new work to reduce team members' stress-related errors whilst maximizing output, and (2) participants preferred having a graph representation for stress levels despite performing better with a text representation. These contributions aim to enhance teamwork, focusing on workers' well-being, quality of task completion, and overall team performance.

4.1 Visualization techniques

AR visualization techniques were developed to support the team leader in assessing the current workflow situation and team members' well-being by providing feedback on the *team members' status*. The *team member's status* is defined as the sum of the team

member’s *task status* and *inner status*. *Task status* refers to all information related to the user’s current, previous, and future tasks. *Inner status* encapsulates one’s well-being-related information, e.g., physiological levels (such as heart rate, body temperature, skin conductance), emotions, fatigue, and stress. For the purposes of this work, only a partial set of *inner status* attributes is examined. Instead, the focus is on measuring how the team leader’s actions put team members under *stress*. In this context, the stress is not directly measured, it is rather calculated from known parameters such as the amount of rest the team leader provides. The formal definition of how stress is determined is presented in Section 4.2.2.

The previous chapter (and the publication arising from this chapter [125]) showed that providing *task status* to team members helped them to know how well others were performing. It can be inferred that *task status* can also help the team leader determine which team member is best suited to be assigned a task. This study shares similarities with prior work where a local worker shares visual cues (gaze, facial expressions, physiological signals, and environmental views) with a remote helper who provides guidance [89], but the collaborative context differs. Indeed, this dissertation specifically focuses on team monitoring and task allocation, while concurrently sharing a worker’s status to understand their actions and well-being. To present the task status and the inner status with AR, the graphical assets must be easy to understand, and avoid occlusion [56]. Both text and visual elements can be used, text must be simple and written on a billboard to contrast with the background [55, 57], and icons, symbols and simple 2D graphic elements can support or replace text in AR-presented information [58]. To answer RQ2.1 and RQ2.2, a set of AR visualizations of *team member’s status* were developed as a set of awareness components with two different presentation styles: Literal (Figure 4.1) and Symbolic (Figure 4.2). The literal style employs numeric and textual presentations of the different attributes of user status information. All numerical and textual information was displayed in white text with a black background, where the symbolic presentation employs graphs and 3D representations. All components are displayed on 2D panels floating around workers to avoid occlusion. A description of each component is as follows:

- **Task Queue** displays the number and the type of tasks a team member has yet to complete. The literal style had four numbers, one for each task type: SYSMON, COMM, TRACK and RESMAN. The symbolic presentation had a virtual shelf that held stacks of each of the different tasks represented in the cube as on the team leader’s table (‘S’ for SYSMON, ‘C’ for COMM, ‘T’ for TRACK and ‘R’ for RESMAN,

see Figure 4.2).

- **Current Task Completion** shows which task a team member is currently performing and its progress. The literal style presents this as a numeric percentage, and the symbolic presentation employs a progress bar.
- **All Task Completion** shows the progress of a team member on a task batch they have received. Both styles employ the **Current Task Completion** visualizations.
- **Task History** shows the number and the type of tasks completed from the start of the work session. Both styles employ scaled-down versions of the **Task Queue** component. The cubes are smaller and closer to each other, maximizing information density within a smaller space compared to the **Task Queue** component.
- **Portion of Time Working** represents the proportion of time a team member spent working since the start of the scenario, and the complement to 100% represents the time spent resting. Both styles employ the **Current Task Completion** visualizations.
- **Success** shows if a team member succeeded or failed their assigned tasks. The literal style presents success and failure as integer values and the ratio of success/-failure as a percentage. Instead of using numbers, the symbolic style presents a disc that fills radially with the success percentage.
- **Score** shows how well a team member completed their tasks. Each task is rated on a scale from 0 to 1 inclusive (see Section 4.2.2 for more details). The component displays a cumulative score since the beginning of the scenario (the sum of all the individual task scores) and the average score per task. The literal style presents the current score as a real number and the score per task as a numeric percentage. The symbolic style only presents the score per task percentage as a disc that fills radially.
- **Stress** shares a team member's *inner status* summarized under the *simulated stress* term. The literal style presents a history of stress levels an operator has been going through, and the current level and value of their *simulated stress*. The written value of the current *simulated stress* is coloured following the stress level (Low - Green; Medium - Yellow; High - Red, see Section 4.2.2 for more details). The symbolic style presents a 2D graph with time as the x-axis and *simulated stress* as the y-axis. The line drawn on this graph takes the colour of the stress level recorded at that time.

The organization of components within panels was refined through pilot experiments,

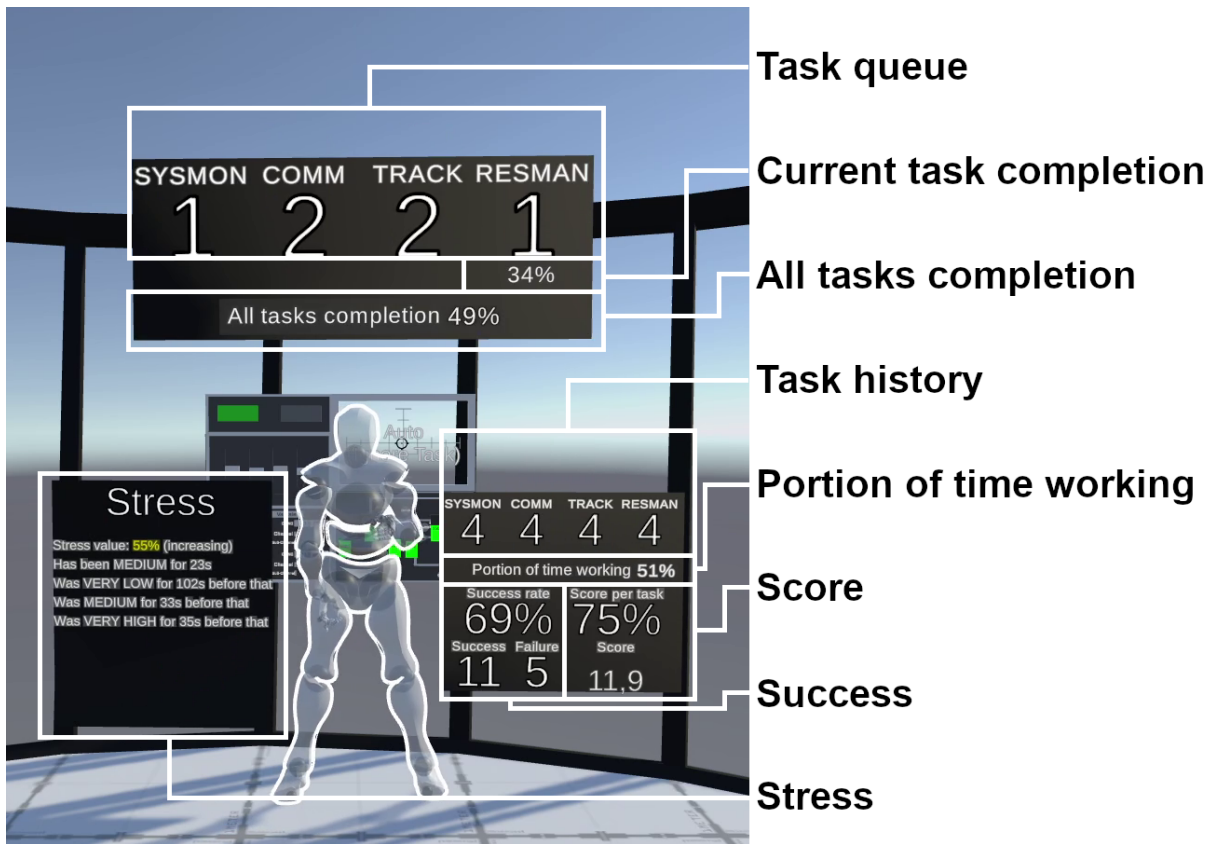


Figure 4.1 – Awareness components with a Literal presentation.

where valuable feedback was obtained. Three main categories emerged based on this feedback: the present and future workload of a team member (comprising Task Queue, Current Task Completion, and All Tasks Completion components), their past performance (including Task History, Portion Of Time Working, Success, and Score components), and their past and current *inner status* (represented by the Stress component). To effectively organize and present this information, a structured approach was chosen. Instead of grouping all elements into a single panel, three dedicated panels were created, each tailored to one of these categories. The final placement and design of these components aimed to achieve two key objectives. Firstly, it sought to minimize overlap between panels of different team members. Secondly, the design was crafted with a focus on improving the overall readability of all components.

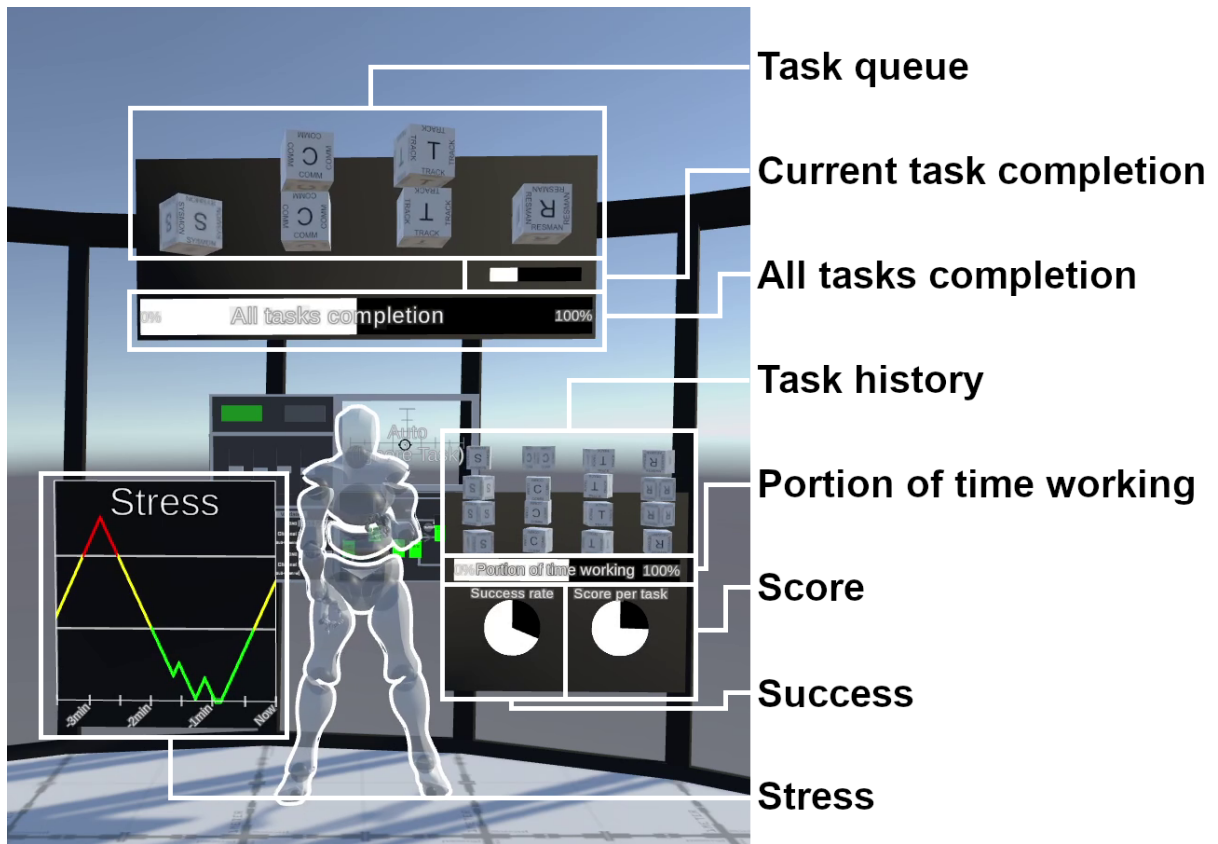


Figure 4.2 – Awareness components with a Symbolic presentation.

4.2 Experimental platform

To evaluate the visualization propositions, a new scene has been added to the experimental platform presented in the previous chapter. This scene enables a user to function as the team leader, assigning tasks to virtual team members, the *operators*, while having AR visualizations of operators' status. *Operators* are part of the experimental platform and were fully simulated to keep the system invariant from one simulation to another. They are virtual team members who have their behaviour influenced across iterations of the simulation by the tasks assigned, the platform then gathers data from a team leader who assigns tasks to this **simulated team**. The experimental platform is in VR, and the AR is simulated in the platform: to deploy a technical experimental platform, a fully controllable VR system guarantees better experimental invariants than having multiple real operating posts built. The remainder of this section presents both the experimental platform and the operator model.

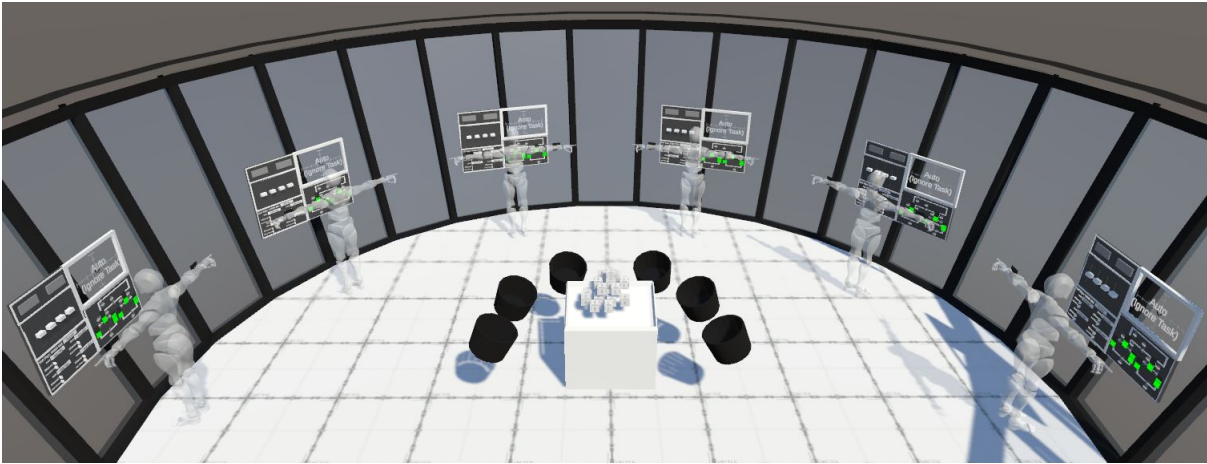


Figure 4.3 – The virtual environment employed in the experiment featured six virtual team members, each assigned a designated black bucket situated between the team member and the leader. These buckets served as receptacles for tasks assigned by the team leader, who interacted by throwing task cubes into them. Positioned centrally within the room, the team leader’s table holds the task cubes they have to assign, surrounded by the six black buckets that have been moved closer to the table.

4.2.1 Prototype

The developed experimental platform allows a participant to perform the role of a team leader facing virtual team members labelled *operators*. The number and placement of operators in the virtual environment can be set or modified depending on the experiment conducted. The system automatically creates tasks that the team leader has to assign to operators. Cubes represent the tasks the team leader has to allocate to operators by throwing the task cube in the corresponding basket of each operator (see Figure 4.3). Cubes with an 'S' are used to represent the SYSMON task, a 'C' for the COMM task, a 'T' for TRACK task and a 'R' for RESMAN task. The system drops a set of tasks onto the table in front of the team leader. The team leader picks up the tasks from the table with either hand and assigns them to the different operators. The sets of tasks are in blocks of 5 to 20 cubes every 30 seconds.

The operators are modelled to perform tasks at different degrees of success, which is represented by the score, a decimal value between 0 and 1 inclusive given to an operator after performing a task, depending on how stressed they are; Section 4.2.2 fully describes this model. The experimental platform integrates the visualization techniques presented in Section 4.1, providing AR-displayed information around each operator, as feedback on the operator’s status. This AR display provides data to inform the team leader’s choice of

an operator to assign a task to, thus optimizing the team’s overall success. The experiment was designed for the participants to receive tasks over time to assign to the operators to achieve the greatest team performance. The team performance was calculated by how well the operators performed the given tasks. The team score is calculated as the sum of the scores of all the tasks performed by the operators. The experimental platform enabled two factors to be manipulated: 1) the presentation of indicators (symbolic and literal) and 2) if *simulated stress* feedback is shown or not shown.

4.2.2 Operator model

Operators are automated virtual team members controlled by the experimental platform. The operators have humanoid avatars to tackle the same occlusion and placement issues we would have in an AR workspace. Their avatar is either controlled by inverse kinematics animation for the four tasks or by skeleton animation when the avatar is idle. The operators virtually perform the four tasks of the NASA MATB-II [129] on a virtual screen interface in front of them, see Figure 4.3 The avatars of the operators replay previously recorded movements with inverse kinematics (using FinalIK). The movement data set comprises more than ten different recordings for each task recorded from a person performing the four MATB-II tasks in a VR setting with the experimental platform. The playback speed for each animation was adjusted to last for ten seconds. If not replaying a recorded animation, the avatar of the operator plays one randomly chosen idle animation among the six skeleton animations from the Mixamo library. Inverse kinematics interpolates the positions of the hands and head to ensure consistently smooth movement when the avatar transitions between recorded movements and other animations [7].

The tasks assigned to operators by the team leader are stored in a task queue. Operators will perform their tasks one after another without resting between them until the queue is empty, following a FIFO (First In, First Out) pattern. When an operator’s task queue is empty, they are on a rest break until new tasks are placed in their queue.

Each operator has a speed multiplier; with a speed of 1.0, an operator will execute a task in 10s (the normalized time for all tasks); with a speed of 1.5, they will execute the task in 6.7s and, with a speed of 0.75, they will execute the tasks in 13.3s. Two operators have a speed multiplier of 0.75, two operators have a speed multiplier of 1.0, and two have a speed multiplier of 1.5.

Operators have a *simulated stress* attribute as the most straightforward indicator of their internal status (normalized to a 0.0-1.0 range). The team leader’s adding a task

to an operator’s task queue progressively increases the *simulated stress* experienced by that operator, labelled as *stress charge*. The total amount of *simulated stress* per task experienced by an operator is not impacted by the speed at which the operator completes the task; thus, the *stress charge* is obtained by multiplying the speed of the operator by the *stress charge* parameter. Operators’ *simulated stress* decreases with time, labelled as *stress cooldown*; all operators have the same rate of *stress cooldown*, another parameter of the experimental platform. The *stress charge* parameter has to be stronger than the *stress cooldown* parameter to increase operators’ *simulated stress* when they work, as their *simulated stress* evolves by the following Algorithm: *As long as the simulation is running, the operator’s simulated stress decreases by the cooldown rate, then it increases by the charge rate if the operator has a task to perform.* This algorithm is also presented with pseudo-code, see Algorithm 1.

```
Data: previous stress value of the operator
Result: current stress value of the operator
while time passes do
  if operator has tasks to perform then
    // increase the stress by the charge rate
    stress = stress + charge * Δt
  end
  // decrease the stress by the cooldown rate
  stress = stress – cooldown * Δt
end
```

Algorithm 1: How stress evolves through time

The experimental platform makes a probabilistic determination of whether an operator is successful for each task. The more stressed an operator is, the more likely they will not succeed with the task. Three different levels of *simulated stress* can be distinguished: LOW, MEDIUM, and HIGH, with two parametrable thresholds to separate them. Previous work investigated how human experience affects their performance [32, 34, 160]. As revealed by psychological research, commonly used human experience models are not realistic [34], partly because the experimental conditions do not reflect reality. Early research suggested that performance increased with physiological or mental arousal, up to an optimal level after which performance decreases [160], being referenced as the Yerkes-Dodson’s law. However, more recent research has revealed the lack of a strong basis for the law and highlighted managerial practices that aim to increase or maintain stress levels in the workplace to enhance employee performance [32]. To enable individuals with

limited or no experience in team management to comprehend, this experiment employed a straightforward model illustrating the impact of operators' stress on their performance. With a LOW level of *simulated stress*, there is a low chance of failure by an operator, and at a HIGH level of *simulated stress*, the operator is almost certain to fail at the task. A parametrable function defines a task's failure probability according to the *simulated stress* level. As a performance measure, a score of 1 minus the failure probability is given to an operator after performing a task. Operators have no preference or skill differences among tasks. Initial conditions of the virtual environments and operators' attributes will be described in Section 4.3.2.

4.3 User study: presenting team members' performance and inner status with XR

4.3.1 Experimental design

A 2×2 within-participants study was conducted to evaluate if the presence of stress feedback (*Stress* or *NoStress*) and which presentation of data (*Literal* or *Symbolic*) best helped the team leader. The study thus compared four conditions: *Literal~NoStress*, *Literal~Stress*, *Symbolic~NoStress*, and *Symbolic~Stress*. The *Literal~NoStress* and *Literal~Stress* conditions were designed to evaluate **RQ2.1** around whether stress improves user performance when information has a *Literal* presentation. This research question is also addressed in a context where information has a *Symbolic* presentation with *Symbolic~NoStress* and *Symbolic~Stress* conditions. The *Literal~Stress* and *Symbolic~Stress* conditions enable the evaluation of the impact of the representation of that stress on user performance to assess **RQ2.2**.

4.3.2 Parameters and initial conditions

Pilot experiments determined the study's parameters and initial conditions. The *stress charge* parameter was set to 2% per second, and the *stress cooldown* parameter was set to -0.1% per second. The threshold between LOW and MEDIUM levels of stress was set to 0.4, and the threshold between MEDIUM and HIGH levels of stress has been set to 0.7. For the failure probability function, the error function [5] shifted and scaled was used, plotted and described in Figure 4.4. The virtual scene has six operators (see Section 4.2.2), who

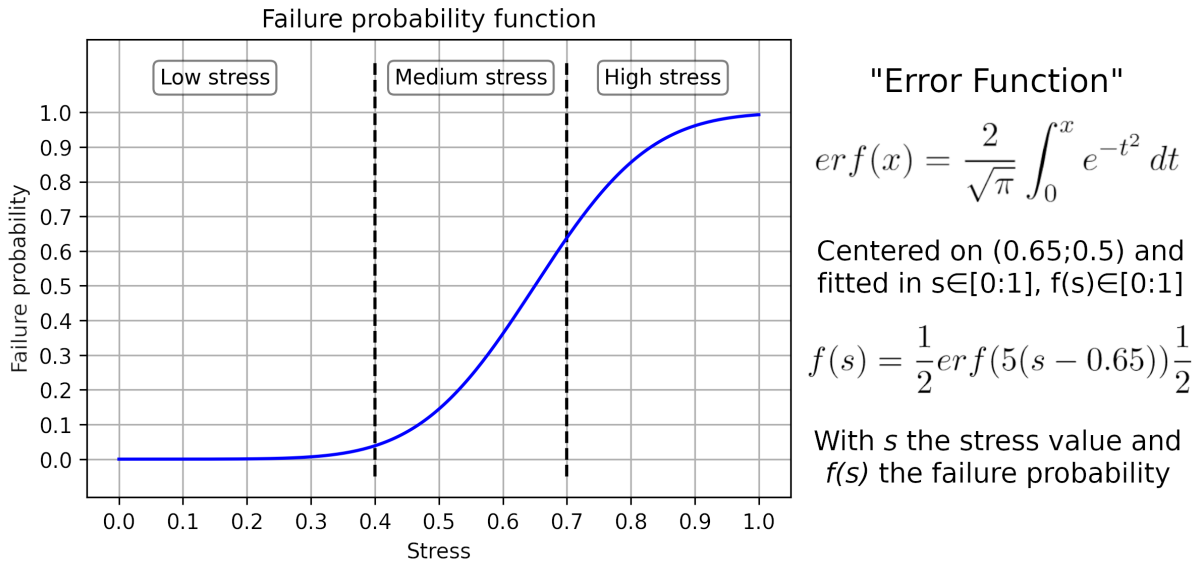


Figure 4.4 – Failure probability function.

are assigned a speed factor, a stress offset, and some initial tasks (see Listing 4.1). At the start of each trial, two operators are randomly chosen to become *slow operators* with a 0.75-speed multiplier, two others are randomly chosen to become *fast operators* with a 1.5-speed multiplier, and the last two operators will stay *normal speed operators* with a speed multiplier of 1.0. At the same time, two operators are randomly chosen to begin with LOW stress (0.3), two others are randomly chosen to begin with MEDIUM stress (0.5), and the two last ones will begin with no stress at all (0.0). The trial then starts by assigning 12 tasks among operators: two operators are randomly chosen to receive one task, two other operators receive two tasks each, and the last two operators are given three tasks each. The random assignment of initial conditions for the operators removes any learning effects between trials on each of the operator’s abilities. In the worst case, there will only be one failure with the initial conditions, which will have minimal impact on overall team performance.

Listing 4.1 – Randomization source code

```
opIndexes = new List<int>(){0,1,2,3,4,5};

// Randomize slow and fast operators placement
opIndexes.Shuffle();
// 2 slow operators
operators[opIndexes[0]].speed = 0.75f;
operators[opIndexes[1]].speed = 0.75f;
// 2 normal speed operators
operators[opIndexes[2]].speed = 1.00f;
operators[opIndexes[3]].speed = 1.00f;
// 2 fast operators
operators[opIndexes[4]].speed = 1.50f;
operators[opIndexes[5]].speed = 1.50f;

// Randomize distribution of initial stress
opIndexes.Shuffle();
// 2 not stressed operators
operators[opIndexes[0]].stress = 0f;
operators[opIndexes[1]].stress = 0f;
// 2 LOW stressed operators
operators[opIndexes[2]].stress = 0.3f;
operators[opIndexes[3]].stress = 0.3f;
// 2 MEDIUM stressed operators
operators[opIndexes[4]].stress = 0.5f;
operators[opIndexes[5]].stress = 0.5f;

// Randomize distribution of initial tasks
opIndexes.Shuffle();
// 2 operators with 1 task
operators[opIndexes[0]].GiveRandomTask(1);
operators[opIndexes[1]].GiveRandomTask(1);
// 2 operators with 2 tasks
operators[opIndexes[2]].GiveRandomTask(2);
operators[opIndexes[3]].GiveRandomTask(2);
// 2 operators with 3 tasks
operators[opIndexes[4]].GiveRandomTask(3);
operators[opIndexes[5]].GiveRandomTask(3);
```

4.3.3 Hypotheses

To answer the two research questions, **RQ2.1 - Does providing information about a team member’s stress status and current workload help team leaders manage a team?** and **RQ2.2 - Which AR visualizations are most effective in helping team leaders understand the status of their team members?** the study assess the following hypotheses:

H1 - *Providing operators’ stress feedback to team leaders improves team performance.* During the training, participants were informed that stress directly impacted team members’ performance, and they were informed on how their actions increased and decreased team members’ stress levels. Providing participants with information on team members’ stress levels will help them to make better decisions, and improve the overall team performance.

H2 - *Team leaders will prefer the presentation of operators’ stress in Symbolic form rather than Literal.* A graph helps to read multidimensional data, and the participants will prefer to read a graph rather than multiple lines of text to have information on the team members’ stress over time.

4.3.4 Data Collection

Experiment independent variables are the presence of stress feedback (*Stress* and *NoStress*) and the presentation mode (*Literal* or *Symbolic*). Experiment-dependent variables are as follows:

- The **Team Score**: sum of the score of all the tasks performed by the operators. The **Team Score** is a real number that can range between 0.0 and 172.0, respectively for a null score and a perfect one.
- The **Trial Duration**: time in seconds the team takes to complete all tasks, the trials have no time limit.
- The answers to the NASA-TLX (raw Task Load index [67]), a survey on six different dimensions: the mental demand, physical demand, temporal demand, the performance, effort, and frustration felt by the participant during the task. Each dimension has been assessed on a five-level Likert scale.
- The preferred condition for each component (what helped them the most).
- The preferred components with the Literal presentation.
- The preferred components with the Symbolic presentation.

Additional data was collected during the experiment:

- The adopted strategy of assigning tasks after every trial.
- A further explanation of the evolution of the participant's strategy at the end of the experiment.
- Participants' opinion on the importance of stress feedback.
- Suggestions of combinations of Literal and Symbolic versions of the components.
- Open remarks (to gain additional insights into the visualizations).

4.3.5 Apparatus

The study was conducted in a quiet room exclusively dedicated to the study for its duration. Protocols to fight against COVID-19 have been deployed (disinfection of equipment, wearing a mask, and such). The experimental platform was run on a VR-ready computer (DELL laptop, i7-10850H, 32GB RAM, NVIDIA Quadro RTX 3000), using an immersive Head Mounted Display (HTC Vive Cosmos) with controllers. The experimental platform was the MATB-II-CVE application, a custom-developed software using Unity 2018.4.30f1, C#, and the SteamVR framework. The Unity project of the experimental platform application is open-access: https://github.com/ThomasRinnert/MATB-II_CollabVR.

4.3.6 Participants

For this study, 24 volunteers were recruited (6 females, 18 males) aged from 18 to 54 years old (Mean: 29.3, SD: 8.4), who were rewarded with gift cards after the experiment. The participant self-reported their handedness (1 left-handed, 23 right-handed), and they rated on a scale from 0 ("Not at all") to 4 ("A lot") their familiarity with and use of video games (Mean: 3.6, SD: 1.2), 3D environments (Mean: 3.5, SD: 1.5) and immersive technologies (Mean: 3.5, SD: 1.4).

4.3.7 Protocol

The participants were first welcomed and asked to read an information sheet. If they agreed to participate, they signed a consent form, these two documents can be found as appendices. They were then informed of the objectives of this experiment: to help team leaders manage their team by being better informed concerning the team members' status

feedback. The participants were then informed how operators work (see Section 4.2.2), particularly how the task score is affected by the operator’s stress level. The Literal and Symbolic presentations of the proposed visualization techniques were then presented to the participants (see Section 4.1), asking them to achieve the best team performance while minimising operators’ stress. Participants were aware that time was not a constraint. The University of South Australia Human Research Ethics Committee approved this experimental protocol (project ID: 204935, available as an appendix).

Training

After the introduction, the participants were equipped with the VR headset and its controllers, and the training phase then started. There were five phases of training: the initial training and a training phase before each trial. During the initial training, participants could experience how to assign tasks to operators. They could ask to retry as many times as they wanted until they were ready to begin a trial. Before each condition, the awareness components were shown to participants, and they could assign some tasks, like during the initial training phase to understand how the awareness components evolved.

Task Assignment Trial

During the experiment, the participant had to complete four trials in the virtual environment of assigning tasks to the six operators. A trial had no fixed duration: 160 task artifacts were given to the participants over approximately 8 minutes (5 to 20 every 30 seconds) for them to assign the tasks to operators. The trials end when all tasks are assigned and completed. This number of tasks had been determined during preliminary pilot experiments, where we investigated if there were enough tasks to place the virtual operators in a high-stress state. The experimental parameters produced tasks that even when assigned with care, operators can reach a point where they are fully stressed. Even though the number of tasks is constant (160), the cubes depicting the tasks are generated to be one of the four MATB-II tasks randomly. The only difference in tasks is the name. The tasks all last the same time range for task completion, and operators have no preferences or skill differences among the four types of tasks. Participants were asked to answer questionnaires between each trial and at the end of the experiment (available as appendices). The experiment lasted for approximately one hour and a half for each participant.

4.3.8 Results

All quantitative data were analyzed following the same process, starting with a Shapiro-Wilk test to check for normality. For normally distributed data, 2-ways ANOVAs were used (after checking that the sphericity assumption was met with a Mauchly test) with Tukey HSD tests ran as posthoc analysis, and for data not following a normal distribution, we ran two different analyses:

1. Both conditions with Literal presentation were aggregated and compared with a Wilcoxon test to the two other conditions with Symbolic presentation, and the same was done for conditions with and without stress feedback;
2. Friedman χ^2 tests were used to check for significant differences between conditions, then pairwise Wilcoxon signed-rank tests were used as a posthoc analysis with an alpha correction to 0.01 to compare the conditions.

Again, when reporting results, the means will be presented followed by the standard deviation, the test statistics and the effect size.

Objective measures

A significant effect of the stress feedback on *Team Score* was found, participants achieved better performance with the *Stress* conditions than with the *NoStress* conditions (*Stress*: score = 119.9 ± 45 ; *NoStress*: score = 97.5 ± 45 ; $W = 266$, $p = 0.0007$, $r = -0.489$, see Figure 4.5). This supports **H1**: providing **stress feedback improves performance**. The presentation alone had no significant effect on *Team Score*. Further analysis showed that the *Literal~Stress* condition led to a significantly higher *Team Score* than the *Literal~No Stress* and *Symbolic~No Stress* conditions (*Literal~Stress*: score = 125 ± 47 ; *Literal~No Stress*: score = 101 ± 46 , $W = 59$, $p = 0.008$, $r = -0.542$; *Symbolic~No Stress*: score = 94 ± 45 , $W = 50$, $p = 0.003$, $r = -0.603$).

Trials had no time limit, that said, the fastest participant completed a trial in 7 minutes and 25 seconds and the slowest did in 17 minutes and 32 seconds. There was no explicit request to complete the experiment as fast as possible, however, in reviewing the overall *Trial duration*, we could observe a significant effect from both factors and an interaction effect (stress feedback: $F(1, 92) = 5.5$, $p = 0.021$, $\omega^2 = 0.039$; presentation: $F(1, 92) = 10.2$, $p = 0.002$, $\omega^2 = 0.080$; interaction: $F(1, 92) = 5.5$, $p = 0.021$, $\omega^2 = 0.039$, see Figure 4.6). The posthoc analysis showed that the *Symbolic~Stress* condition led to a longer *Trial Duration* compared to all other conditions (*Symbolic~Stress*: mean =

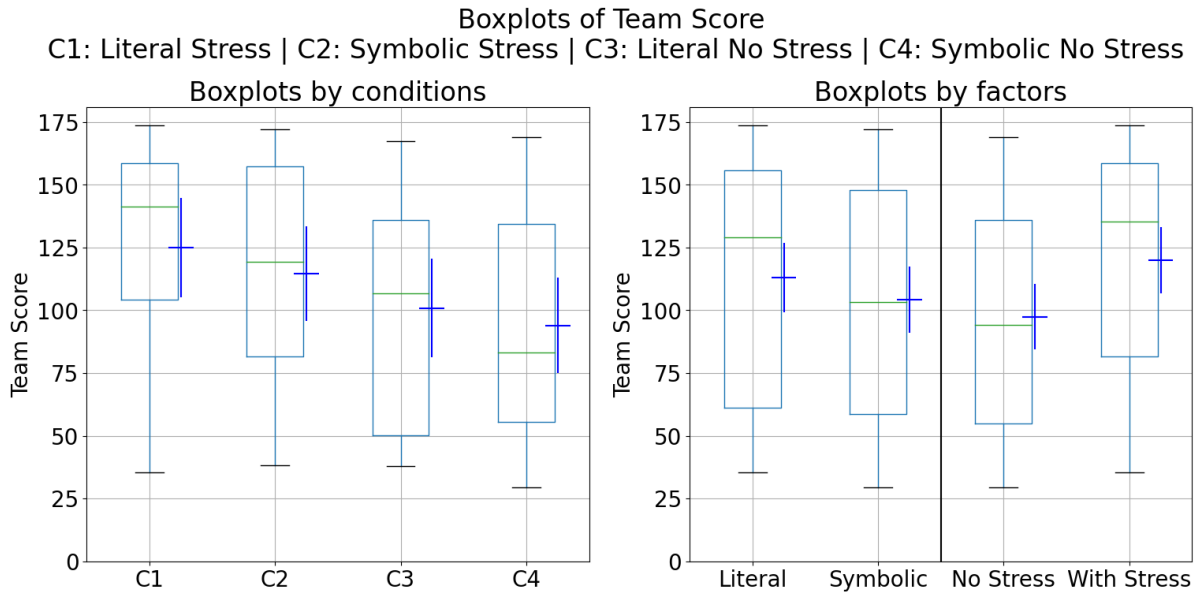


Figure 4.5 – Sum of all individual scores obtained by operators. The boxes in the figure represent the quartiles, with the median indicated by a green line. Additionally, blue horizontal lines depict the means, while blue vertical lines illustrate the corresponding confidence intervals.

766 ± 71 sec; *Literal~NoStress*: mean = 648 ± 121 sec, $p = 0.001$; *Literal~Stress*: mean = 648 ± 91 sec, $p = 0.001$; *Symbolic~NoStress*: mean = 666 ± 126 sec, $p = 0.007$).

In reviewing *Time spent assigning tasks*, both factors had a significant effect but with no interaction effect (stress feedback: $W = 379$, $p = 0.032$, $r = -0.31$; presentation: $W = 349$, $p = 0.013$, $r = -0.357$; see Figure 4.7). Participants spent more time assigning tasks in the *Stress* conditions than in the *NoStress* conditions (*Stress*: time = 422.7 ± 171.7 ; *NoStress*: time = 372.3 ± 162.5). On the other hand, participants spent more time assigning tasks in the *Symbolic* conditions than in the *Literal* conditions (*Symbolic*: time = 416.6 ± 174.7 ; *Literal*: time = 378.4 ± 161). As the Friedman test did not produce significant results, no pairwise Wilcoxon tests were run.

Performance is not just a numerical and empirical measure; it depends on criteria imposed by the context. In a collaborative context where time is not a precious resource, *Team score* would be the most relevant way to assess performance, but if time has to be considered (even while not being a solid constraint), it can be interesting to look at the ratio of *Team score* by *Trial duration*.

Considering *Time performance*, participants performed significantly better in the *Stress* conditions than in the *NoStress* conditions (*Stress*: performance = 10.1 ± 3.7 ; *NoS-*

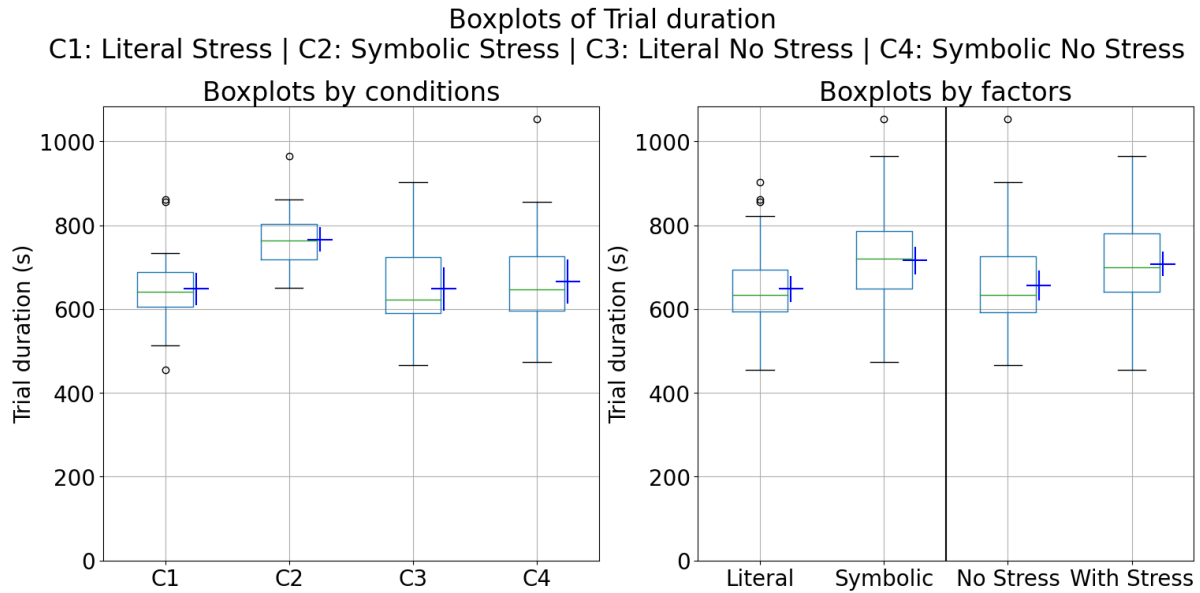


Figure 4.6 – Time (in seconds) trials lasted. The boxes in the figure represent the quartiles, with the median indicated by a green line. Additionally, blue horizontal lines depict the means, while blue vertical lines illustrate the corresponding confidence intervals.

tress: performance = 8.6 ± 3.1 , $W = 324$, $p = 0.006$, $r = -0.396$). Participants also performed significantly better in the *Literal* conditions than in the *Symbolic* conditions (*Literal: performance* = 10.2 ± 3.6 ; *Symbolic: performance* = 8.5 ± 3.0 , $W = 198$, $p = 0.00003$, $r = -0.605$). Further analysis showed that the *Literal~Stress* condition led to a significantly higher *Timed performance* than all other conditions (*Literal~Stress: performance* = 11.3 ± 3.8 ; *Symbolic~Stress: performance* = 8.9 ± 3.1 , $W = 31$, $p = 0.0003$, $r = -0.742$; *Literal~No Stress: performance* = 9.0 ± 3.1 , $W = 48$, $p = 0.003$, $r = -0.617$; *Symbolic~No Stress: performance* = 8.2 ± 3.1 , $W = 34$, $p = 0.0004$, $r = -0.719$).

Questionnaires

In reviewing the overall NASA-TLX score, no significant difference was found. However, a detailed assessment of the questionnaire revealed participants felt significantly less mental demand, effort and frustration when provided with stress feedback (mental demand - *Stress: demand* = 3.48 ± 0.92 ; *NoStress: demand* = 3.77 ± 1.04 , $W = 88$, $p = 0.037$, $r = -0.301$; effort - *Stress: effort* = 2.96 ± 0.94 ; *NoStress: effort* = 3.38 ± 0.98 , $W = 132$, $p = 0.009$, $r = -0.376$; frustration - *Stress: frustration* = 2.19 ± 0.96 ; *NoS-*

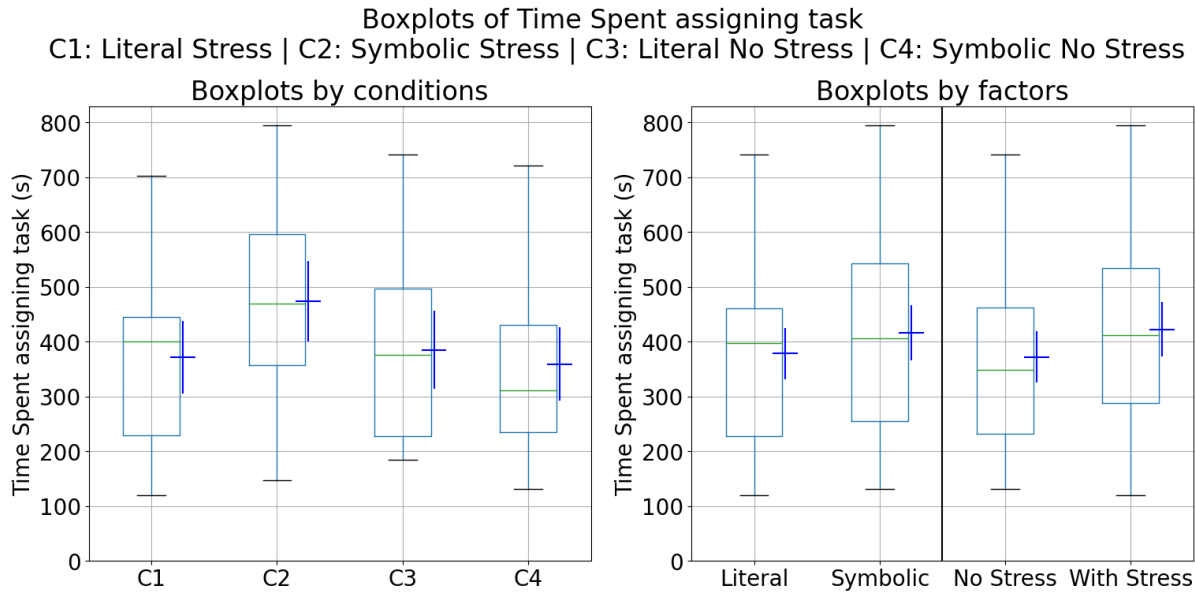


Figure 4.7 – Time (in seconds) participants spent assigning tasks to operators (time participants held a task artifact in their hands). The boxes in the figure represent the quartiles, with the median indicated by a green line. Additionally, blue horizontal lines depict the means, while blue vertical lines illustrate the corresponding confidence intervals

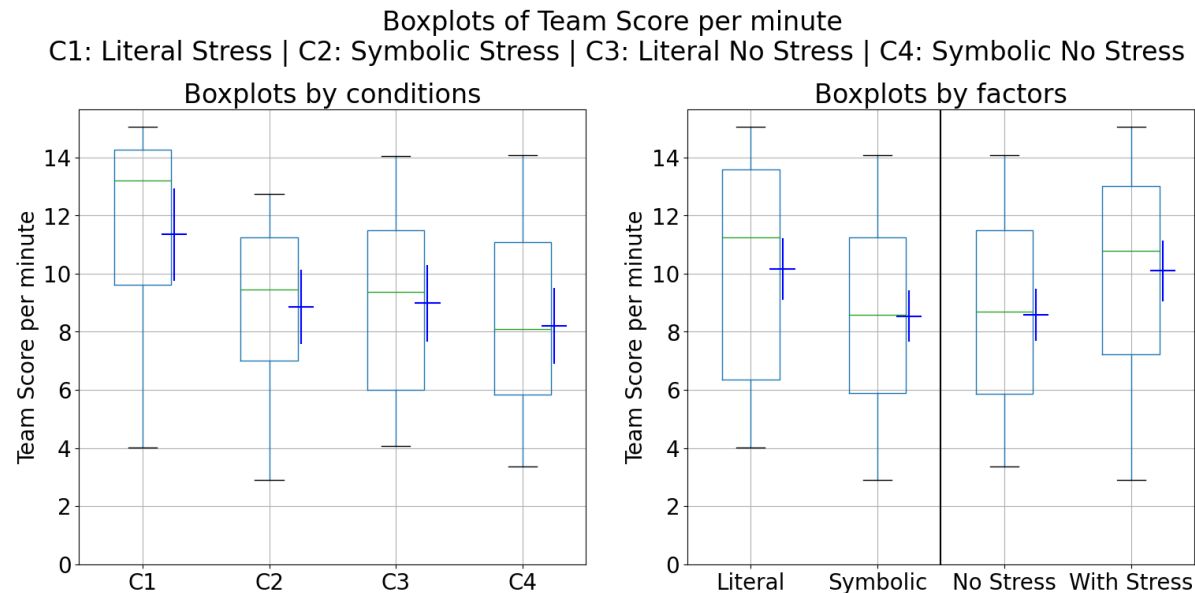


Figure 4.8 – Team score divided by the trial duration (in minutes). The boxes in the figure represent the quartiles, with the median indicated by a green line. Additionally, blue horizontal lines depict the means, while blue vertical lines illustrate the corresponding confidence intervals

tress: $frustration = 2.46 \pm 1.29$, $W = 65$, $p = 0.040$, $r = -0.297$).

After each trial, participants were asked to explain their task assignment strategy with open feedback. It revealed that when stress feedback was not provided, the main focus was on the Success component when participants needed to choose who to assign a task to, as an indirect way to assess operators' stress and chances to succeed in tasks. Eighteen participants reported doing so after the *Literal NoStress* condition and 17 after the *Symbolic NoStress* condition. Otherwise, the Stress component was the main focus when available. Ten participants stated that their strategy was based on the Stress Component after the *Literal Stress* condition and 16 reported the same after the *Symbolic Stress* condition. Having operators' stress feedback, participants aimed at assigning tasks to operators with a LOW or MEDIUM stress level. Sixteen participants reported doing so after the *Literal Stress* condition and 12 after the *Symbolic Stress* condition. The presentation seems to have little effect on the task assignment strategy except for the stress component: more participants reported focusing on the stress indicator when it had a Symbolic presentation than a Literal one, which supports **H2**. For changing strategies, 22 participants changed their strategy between the trials, 14 reported that it was due to the presence of stress with no further explanations, 9 stated that it was because they focused on the Stress component when it was available, and 9 explained that without stress feedback they focused more on the Success component.

In the final questionnaire, participants had to choose which components they found most helpful for each condition. The only significant difference is for the stress component: participants preferred having it displayed with a *Symbolic* presentation, which also supports **H2** ($\chi^2(1) = 6.0$, $p = 0.014$).

An open-ended question asked participants to share their points of view on the *Literal* and *Symbolic* presentations of the awareness components (listed in Section 4.1). Regarding the *Symbolic* presentation, 15 participants reported that they liked the Stress component, and 5 said that this presentation eased their understanding of the data. For the *Literal* presentation, 5 participants said they enjoyed the Success component, 6 the Score component, 5 stated that the written numbers were a perk of the Literal presentation, and 6 reported that it was easier to understand the data with this presentation.

Asked if they felt that having stress feedback is essential, all participants answered "yes". They were then asked to explain their answer, and what 11 participants reported was that having stress feedback helps to get a better score. One participant explicitly mentioned that having stress feedback was better than determining the stress level from

other components.

In evaluating the possibility of Hybrid components (as a mix of Literal and Symbolic presentations), participants were asked which Hybrid components they may find helpful. Some participants suggested not doing Hybrid presentations of some components and keeping a Literal presentation. Conversely, some participants suggested keeping some components with a Symbolic presentation. No strong tendencies could be identified except for the Task Queue and the Stress components. Among participants having an opinion on the Task Queue component, 6 of them recommended keeping it with a *Literal* presentation, 2 recommended to keep a *Symbolic* presentation, and only 1 suggested changing it to a *Hybrid* component. Opinions concerning the Stress component confirmed the preference for the Symbolic presentation by 11 participants mentioning it; however, 7 participants still suggested turning it to a Hybrid component, with only 1 suggesting keeping it with a Literal presentation.

4.3.9 Discussion

Study outcomes

Results showed that stress feedback significantly improves user performance, supporting **H1**. Stress feedback also resulted in changes to the participants' task assignment strategy. Participants mainly focused on the stress level of operators as it was their primary way to ensure better performance. When the participants did not have stress feedback, they had to conjecture the stress level of operators, having their judgment based on other indicators. With stress feedback, the participants found the process easier to manage the stress level of operators. Overall, most participants could monitor their operators' well-being, which led to better team performance in our system. Providing operators' status feedback to team leaders is more direct and efficient than having them assess how well their team is via performance measures. For future AR information displays to team leaders, the AR information should contain the stress level information of the team members who could potentially receive workload.

Given that a stress indicator improves team performance, the question is which stress presentation provides the most improvement. The results showed that the literal presentation of stress gave a better score, but the participants preferred the symbolic presentation, supporting **H2**. Based on user feedback, some of the AR information (the Success and Score components) presented to the team leader is more understandable with a literal

presentation due to the presence of numbers and the accuracy they bring. Other AR information, such as stress, was easier to understand with a symbolic presentation because it gives a better understanding of the evolution of the value and a global idea of the value. The *Literal Stress* condition was the best performance without the downside of being longer than the *Symbolic Stress* condition. Indeed, the analysis of the participants' strategy explanations revealed that whilst participants did not focus on time, the symbolic presentation of the stress component was easier and quicker for them to comprehend and complete their tasks, thus, before assigning tasks, participants waited for the stress level of operators to get lower than with the literal presentation. Another factor is that the graph takes more time to read than the *Literal Stress* panel and the other literal indicators. This experiment did not put time pressure on participants to allow inexperienced people to take part in the study with only basic training for the task. To further study the effect of the presentation style and the presence of stress feedback on the trial duration, a future study would propose a similar task to people with a managing background.

These observations suggest that collaborative setting designers provide both literal and symbolic presentations of information to team leaders. Indeed, the literal information leads to better performance being more precise and processed faster, and the symbolic presentation information is preferred and is enough to get a rough idea of the information at a glance. Pursuing research on sharing people's status should investigate hybrid presentations, to take advantage of both literal precision and symbolic abstraction.

Limitations

There are some limitations to this study. Only two levels of abstraction of the information were compared; a team of virtual operators was used; the team leader could see the team members or at least an avatar of theirs; the duration of the experiments.

While the study focused on comparing two extremes in terms of abstraction levels in visualizations, it is important to acknowledge the limitations of this approach. The continuum of abstraction offers numerous possibilities, but the goal was to highlight the advantages of each extreme to later recommend a suitable approach. Both literal and symbolic information, as evidenced by quantitative results and participant feedback, demonstrated their respective benefits. Consequently, a balance between presenting raw information textually and offering abstracted information through symbols is recommended, a balance that has to be adapted to specific use cases.

The study investigated the impact of different feedback provided to a team leader

with a virtual team where team members were simulated in the simple Operator Model presented in Section 4.2.2. While the experimental setup allowed us to gain valuable insights, it is essential to consider the potential limitations in generalizing the findings to real-world scenarios with human teams and authentic stress measures. Would the same effects of the indicators' presentation and stress feedback be observed in a real team of humans with real stress measures, would the team leaders adopt the same strategy, and would they feel the same empathy towards the team members? This experimental design intentionally simplified the way stress affected the operators for ease of understanding among participants. However, this simplicity may not fully capture the intricacies of how real stress influences human performance and team dynamics. In this experimental context, the lower limit of the failure probability occurred when stress levels were at the lowest. This differs with theories such as the 'Flow Theory' [34] and 'Yerkes-Dodson's law' [160], suggesting that human performance tends to peak under moderate stress levels rather than low stress. To address the limitations of the current study, a crucial next step would involve conducting experiments with human operators and utilizing physiological sensors to accurately measure stress levels. This approach would offer a more realistic understanding of how stress influences human performance in team settings. Importantly, readers should interpret these findings with the awareness that the simulated stress in our study might not fully capture the nuances of real-world stress, and the extrapolation of results to human teams requires cautious consideration of these experimental constraints.

An additional limitation of the study was that team leaders had visibility of operators; however, the collaborative presence was not systematically measured. The ability of team leaders to visually perceive operators through avatars during the study may have influenced the dynamics of the interaction, creating empathy toward the operators. This empathetic connection might have been further accentuated in the presence of stress feedback, especially when presented graphically. During the study, a subset of participants explicitly reported heightened assertiveness tied to their empathetic response, particularly in situations where stress feedback was incorporated, and even more so with graphical representation. This limitation is crucial to acknowledge as it introduces a variable that may have influenced the team leader's behaviour beyond the specific measured factors. The absence of a systematic measurement of collaborative presence makes it challenging to isolate and quantify the impact of this variable. Consequently, readers need to consider this potential influence when interpreting and generalizing the results of our study. Future research could explore this aspect more explicitly, incorporating measurements of collabo-

rative presence to further understand its role in the dynamics of team interactions within the context of AR-supported environments.

Another limitation of the study pertains to the constrained time allocated to each participant during the experiments. While one hour may seem relatively brief for an investigation into workload balancing and stress management, longer experiments that delve deeper into these aspects could offer valuable insights. However, extending the duration of experiments poses challenges. In fields such as AR VR, one hour is a standard duration, and surpassing this timeframe can be impractical for various reasons, including participant availability and associated costs. Moreover, spending more than an hour in VR raises ethical concerns due to potential mental and physical stress. Despite these limitations, these findings hold relevance for longer team management scenarios. Incorporating workers' inner status feedback is expected to consistently benefit team leaders in making nuanced decisions when assigning workload to a team. While the graphical representation of workers' stress may prove advantageous in longer cases, as suggested in the Study Outcomes section, the recommendation is to maintain a balanced approach by combining both textual and graphical information for a more comprehensive design choice. For future research, it would be valuable to explore longer experiments conducted in a physical setup with human teams to validate and extend our assumptions.

4.4 Conclusion

In answering **RQ2.1** and **RQ2.2**, this chapter presents three contributions: a set of visualization techniques for team leaders to present members' stress and workload to help manage allocating tasks; a study evaluating the effectiveness of the proposed visualization techniques for team leaders; and an open-access Unity collaborative VR experimental platform we developed: MATB-II-Collab.

The study shows that different presentations of status information and how team members cope affect team performance with a **simulated team**. Investigating the effect of providing feedback on the users' inner status, the study revealed that it enhances team performance and potentially improves how team leaders consider team members' status. This shows that people might have to change how they manage teams to achieve better team performance and members' well-being. Indeed, providing users' status to team leaders should be highly considered in works where team members must perform their tasks reliably with little to no mistakes. The comparison conducted between *Symbolic*

and *Literal* presentations of visual cues suggests that the *Literal* presentation of inner status will achieve better performance, even if people prefer the *Symbolic* presentation. The raw performance information presented to a team leader is more understandable with a *Literal* presentation due to the presence of numbers and the accuracy they bring. On the other hand, more complex information, such as inner status feedback, seems more straightforward to understand with a *Symbolic* presentation due to the abstraction this presentation provides.

These contributions' implications for future research will be further explored in the general conclusion of the dissertation. Based on the findings presented here, the subsequent chapter investigates the potential impact of sharing a prediction of the future inner status of team members. Simultaneously, explorations for an optimal level of abstraction of shared information continue, with the next chapter proposing an assessment of two abstraction levels for both current and predicted inner status indicators. Additionally, the sharing of task-related status among team members persists, albeit with a novel approach utilizing a *Hybrid* presentation format that capitalizes on the advantages of both *Literal* and *Symbolic* presentations. This shift aims to focus the investigation on inner status dynamics while maximizing informational clarity of performance feedback.

PREDICTION OF INNER STATUS EVOLUTION FOR TASK ASSIGNMENT

The conclusion of the previous chapter emphasizes the relevant role of sharing inner status information as a way to bolster both team performance and members' well-being. Taking this concept a step further, this chapter explores the effects of providing team leaders with insights into the current and future status of each team member in extended reality. Integrating the same simulated stress model for virtual team members, new visualizations are proposed to further empower team leaders to make informed decisions when allocating tasks, considering both the present state and anticipated evolution of team members' statuses. This approach aims to optimize decision-making processes and contribute to the continuous improvement of teamwork dynamics.

This chapter builds upon the previous one, focusing on presenting XR information to team leaders. However, the emphasis now lays on the level of abstraction for inner status data and its prediction. In this context, both raw and abstract information concerning a team member's performance is presented to the team leader, establishing an effective baseline for task assignments within the team. While the prediction of a team member's stress evolution is not explicitly examined within the scope of this study, previous research has demonstrated its feasibility using physiological sensors and artificial intelligence [10, 54]. To assess the impact of presenting such predictions to a team leader, a simulated team is employed, providing a controlled environment with fully predictable and manageable stress evolution.

This chapter explores the second research question **RQ2 – What are the elements helping leaders to understand their team members' status and how to present them?** In addition to the questions investigated in Chapter 4, it introduces a new dimension with **RQ2.3 - Does sharing a prediction of the evolution of team members' status with XR help their leaders to efficiently balance the workload?** This chapter also addresses the third research question **RQ3 – How should the data be**

abstracted to better understand the team members' status? In particular, it refines this question in a more precise question with **RQ3.1 - What level of complexity is optimal for abstracting the inner status data?** This aims to identify the most suitable level of complexity for abstracting inner status data, a crucial factor in enhancing comprehension and usability within extended reality environments.

The main contribution of this chapter is a new user status visualisation. This visualization is an AR halo that presents team members' current and future stress levels, replacing the stress graph and history. The AR halo comprises three layers (see Figure 5.1): the first denotes the current stress level, the second predicts the stress level a team member will reach after completing their assigned task, and the third layer illustrates how the prediction would change if the team leader assigned additional tasks. Each layer is colour-coded based on corresponding stress levels. The primary aspect of this contribution is to enhance team leaders' understanding of their team members' mechanisms of dealing with stress from work. The AR halo aims to facilitate a balanced approach, enabling team leaders to efficiently manage work tasks while fostering a healthy and productive working environment. The immersive environment and operator model from the previous chapter are employed in a study to evaluate this contribution.

The first section of this chapter details the stress halo's design and the performance indicators' update. The second section presents the evaluation of the stress halo with a user study.

5.1 Visualization techniques

Expanding on Chapter 3, which demonstrated the effectiveness of providing team members with *task status* to enhance their awareness of mutual performance, Chapter 4 furthered these advantages, showing that sharing *inner status*, such as stress, with team leaders not only assisted in determining the best-suited team member for a task but also led to a significant increase in overall team performance. This section will begin by introducing a novel visualization technique designed to forecast the future stress levels of team members. Following this, the chapter will explore enhancements to the indicators introduced in Chapter 4, aiming to leverage the combined advantages of both *Literal* and *Symbolic* presentations of information.

5.1.1 Stress Halo

Multiple ways to measure inner status exist, whether directly with sensors or indirectly by aggregating multiple sensors' data with artificial intelligence [93]. The choice of addressing *inner status* under the *stress* notion was kept, as it provides a straightforward way to reference it, particularly for individuals with limited experience in teamwork management and well-being monitoring. The stress had two different presentations: a graph plotting stress along elapsed time and a textual history showing the current exact stress value and the stress levels visited in the past (and how much time stress stayed in that level). As feedback on *inner status* was the most impactful indicator to improve team performance, the investigations here take a step further with predicting the evolution of the *inner status*.

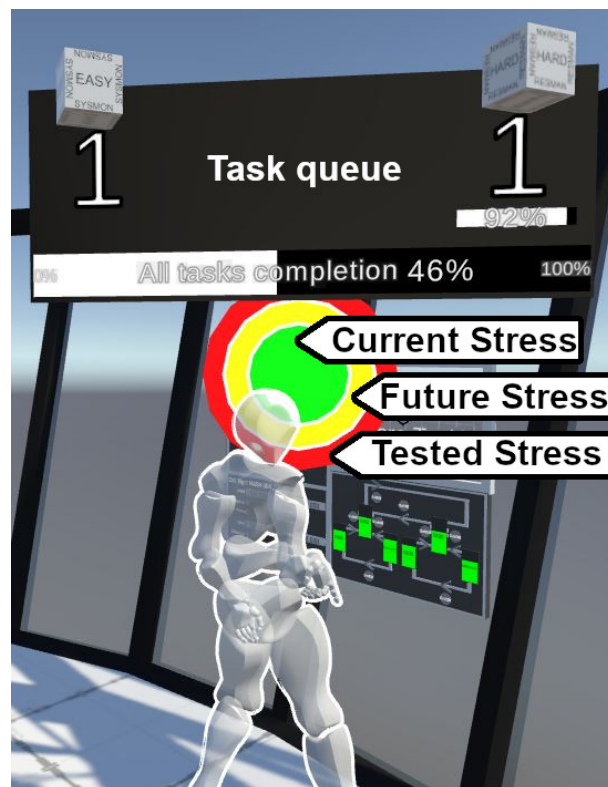


Figure 5.1 – Stress halo depicting **Current**, **Future**, and **Tested** stress. The **Current Stress** is represented by the inner disc, while **Future Stress** appears as the first ring. **Tested Stress** is shown as an outer ring only when the team leader assigns tasks.

The goal is to measure if providing an estimation of the future inner status of a worker could help a team leader to better balance the workload among their team members. The

colour information was reported to be the principal focus on both Literal and Symbolic presentations of the *inner status*, the design of the new *inner status* indicator thus sought to be as simple as possible, involving colours only. The new indicator is composed of three layers, as depicted in Figure 5.1:

- **Current Stress**: a central disc showing the current stress level. The feedback for current stress levels, represented by the inner disc, changes colour as stress crosses predefined thresholds.
- **Future Stress**: a first ring around the disc changing colour to indicate the predicted stress level the worker will reach after finishing their tasks. The computation and gathering of such prediction can be achieved in several ways depending on the applicative context. The computation and gathering of these stress predictions can be achieved using various methods, depending on the specific context of the application. For example, in the study reported in Section 5.2, which employs a simulated team, stress prediction is obtained by pre-computing time steps using the operator model detailed in Section 4.2.2. This model considers working speed and resting time to forecast the worker’s stress levels accurately.
- **Tested Stress**: a second outer ring, visible during task assignment, shows how the prediction of the first ring would change if the task were assigned to the worker. The outer ring appears while the team leader assigns tasks, in the study reported in Section 5.2, it starts when a participant grabs one or more task artifacts and ends when they no longer hold artifacts. The stress level displayed is the one that the **Future Stress** prediction would change to if the tasks the team leader holds were added to the task queue of the worker. This last layer allows team leaders to review or reconsider their decisions when assigning tasks.

In Chapter 4, stress was a continuous value that could be translated into three different levels: low, medium and high. Whilst the number of three levels was an arbitrary choice motivated by both the simplicity of having a small number and the minimum complexity that three levels bring, this chapter presents the investigations towards an optimal abstraction (i.e. number of levels) of the *inner status*. Keeping three levels as a baseline with three colours: green, yellow and red respectively for low, medium and high levels of stress, two intermediary levels were added, see Figure 5.2. The intermediary levels are presented with hatched textures, with the colours of the adjacent levels. The low-medium level thus has a green-yellow hatched texture and the medium-high level paints the components with a yellow-red texture.

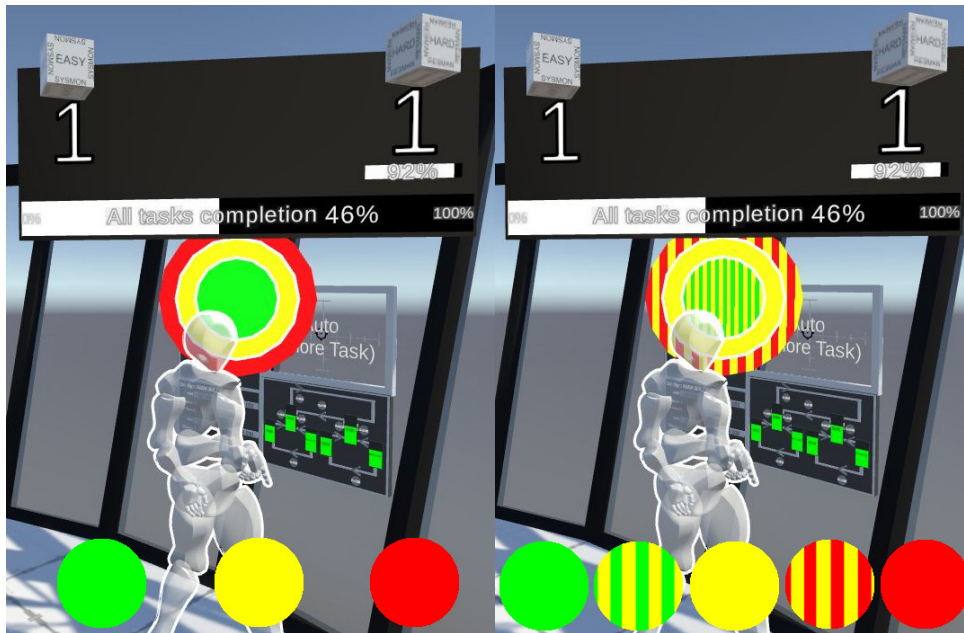


Figure 5.2 – Two color schemes for the stress halo: one with three colors representing low (green), medium (yellow), and high (red) stress levels; and another with five colors, adding two intermediate levels — medium-low (yellow with green hatches) and medium-high (yellow with red hatches).

The placement and appearance of this component were chosen after some prototype testing. In early development, it was envisioned that the *inner status* feedback could be presented as an aura enveloping the workers’ avatars. When giving a glance at the workers, the head of their avatars is a point attracting the eye, hence the design choice of placing the studied component as close as possible to the head. To ensure the adaptability of the visualization technique across various XR settings, the selected choice was a halo positioned behind the avatars of the workers, with the inner circle dimensioned for clear visibility.

5.1.2 Update of the task status components

Aligning with the previous chapter’s recommendations to offer feedback on both *task* and *inner status* to team leaders, the XR visualization techniques of task status are improved. While maintaining the usage of 2D floating panels for clarity and simplicity [55, 56, 57, 58], the novelty relies on displaying the *task status* through both Literal and Symbolic presentations, as depicted in Figure 5.3, to benefit from both presentation modes’



Figure 5.3 – Task status components with a *Hybrid* presentation to benefit from both *Literal* and *Symbolic* advantages.

advantages. A description of the new components is presented below:

- **Task Queue** displays the number and the type of tasks a team member has yet to complete. A virtual shelf holds the different tasks represented with the same cubes as on the team leader's table (see Figure 4.3), the quantity of tasks are represented with a written number under the tasks cubes, instead of piling them up as in the previous chapter.
- **Current Task Completion** shows which task a team member is currently performing and its progress. A numeric percentage is written over a progress bar.
- **All Task Completion** shows the progress of a team member on a task batch they have received, employing the **Current Task Completion** visualizations.

Team Performance provides essential text-based information on the team score, remaining tasks in the session, and time elapsed. This component plays a crucial role in the overall investigations aimed at enhancing performance through improved perception and understanding of collaborative activity. In these studies, the performance adheres to the extensible operator model explained in the previous chapter. A perfect score is achieved when an operator maintains a low stress level, and the team score aggregates individual scores. The significance of the team score is underscored by the maximum achievable score when all tasks are completed flawlessly.

To focus on the inner status feedback, some task status indicators were dropped. The four past performance components – **Task History**, **Portion of Time Working**, **Success**, and **Score** – are consolidated into a single **Team Performance** indicator. This indicator is displayed at the centre of the workspace, allowing team leaders to easily assess their team's overall performance at a glance, see Figure 5.4.

5.2 User study: presenting the prediction of the team members' inner status with XR

5.2.1 Experimental Design

A 2×2 within-participant design was used to evaluate the impact of the prediction of stress feedback (*Prediction* and *No Prediction*) and number of abstraction levels (3 or 5) on the team leader's ability to balance the workload among their team members and the team performance. Participants acted as team leaders using the same experimental

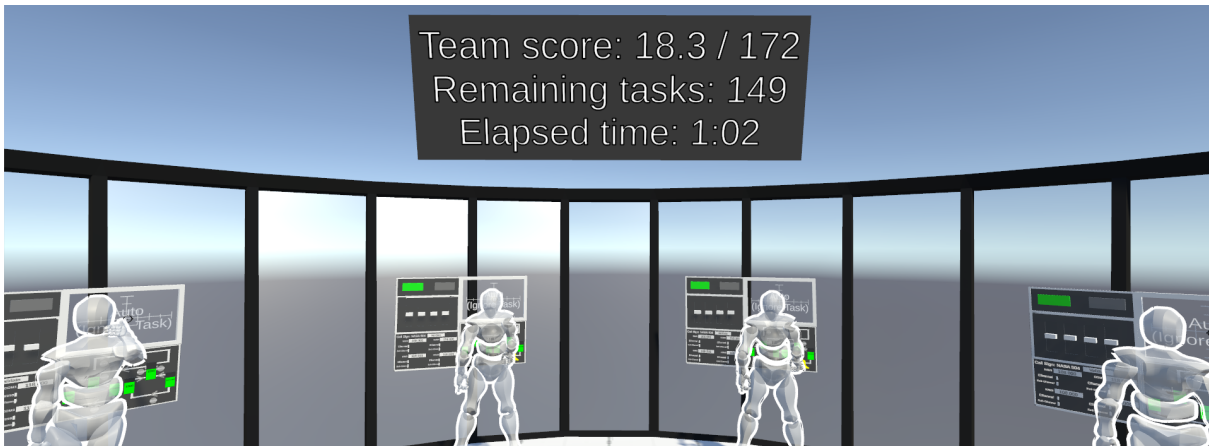


Figure 5.4 – Panel situated at the centre of the workspace to provide feedback on the team performance.

platform employed in the previous study. The only difference with the experimental platform used in the previous study is the introduction of some task assignment complexity. In this study, tasks are no longer differing only in name but are now either categorized as *simple* or *difficult*. As the participants are told at the beginning of the experiment, a *simple* task required the same amount of time for completion by a virtual worker as in the previous study (10 seconds for a virtual worker with a normal speed attribute). In contrast, a *difficult* task required twice that time (20 seconds).

5.2.2 Hypothesis

H1 - *Providing a prediction of workers' future stress levels to the team leader improves the team's performance.* The team performance is calculated as the sum of individual successes on assigned tasks, making it dependent on maintaining optimal well-being among all members. While the definition of this optimal level may vary depending on the context, in this study, it is defined by the operator model as the lowest possible level of stress. Therefore, the closer the stress level is to zero, the better the performance. Providing a prediction of workers' future stress levels to the team leaders helps them better assess the situation by creating more awareness of collaboration. With this improved understanding of the situation, team leaders can better balance the workload among their team and thus improve the outcomes of global teamwork.

H2 - *Providing five levels of stress rather than three improves the team's performance.* With a greater number of levels of stress, the team leaders' understanding of the well-

being of their team members is more accurate. Keeping the inner status of workers closer to an optimum leads to better individual performances and thus better overall team performance. The investigations here focus on comparing five levels to three levels as such gain of accuracy should help to make better decisions only up to a certain level, where increasing the number of levels would only bring confusion.

5.2.3 Data Collection

Throughout the experiment, quantitative data is extracted from action history and logs. Qualitative data is gathered via questionnaires, either at the end of a trial to assess individual conditions or at the end of the experiment to compare conditions. A complete list of the data collected is as follows:

- The team score, a real ranging from 0.0 to 172.0, is the sum of the score of all the tasks performed by the operators throughout a single trial.
- The trial duration is measured at the end of a trial and represents the time in seconds it takes for the participant to lead their team to complete all tasks.
- The portion of time worked represents the percentage of time operators spent performing tasks rather than resting over a trial. Individual values are measured for each operator and then averaged to calculate the measure.
- Assessment of the components (Task Status, Current Stress, Future Stress, Tested Future Stress) regarding their effectiveness in informing task assignment decisions, using five-level Likert scales.
- The answers to the NASA-TLX (Task Load index [67]), a survey on six different dimensions: the mental demand, physical demand, temporal demand, performance, effort, and frustration felt by the participant during the trial. Each dimension has been assessed on a five-level Likert scale.
- Participants' assessment of their capability to identify the slow and fast operators along a trial on a five-level Likert scale.
- Participants' written explanation of the adopted strategy of assigning tasks after every trial.
- At the end of the experiment, participants were asked to report:
 - Their preferred number of abstraction levels as a binary choice.
 - A written explanation of the evolution of their strategy for task assignment to operators.
 - A written opinion on the importance of current and future stress feedback.

— Open remarks to provide additional insights into the visualizations.

5.2.4 Apparatus

The same room, computer and head-mounted display dedicated to the previous study were used to conduct this new one. Again, protocols to fight against COVID-19 were deployed (disinfection of equipment, wearing a mask, and such). The experimental platform still was the MATB-II-CVE application (Unity project available at: https://github.com/ThomasRinnert/MATB-II_CollabVR).

5.2.5 Participants

The study welcomed 28 volunteers (9 females, 19 males) aged from 19 to 37 years old (Mean: 26.7, SD: 4.5), who were rewarded with gift cards after the experiment. The participant self-reported their handedness (1 ambidextrous, 5 left-handed, 22 right-handed), and they rated on a scale from 0 (“Not at all”) to 4 (“A lot”) their familiarity with and use of video games (Mean: 3.6, SD: 1.3), 3D environments (Mean: 3.9, SD: 1.2) and immersive technologies (Mean: 3.5, SD: 1.4). Given their good familiarity with video games, 3D environments, and immersive technologies, participants quickly acclimated to the experimental platform interactions, demonstrating a clear understanding of the assigned task.

5.2.6 Protocol

Following the established protocol from the preceding study, participants were welcomed and provided with a detailed explanation of the experiment’s procedures. This included an overview of the task they would be required to perform and an introduction to the operators’ mechanism. Subsequently, participants were requested to sign a consent form (available as an appendix). A particular emphasis was placed on the primary objective of the study: achieving optimal team performance while minimizing operators’ stress. Participants were explicitly informed that time constraints would not factor into their task completion. The University of South Australia Human Research Ethics Committee approved this experimental protocol (project ID: 204935, available as an appendix).

Training

After the introduction, participants were provided with the VR headset and its controllers. They were then assisted in adjusting them, marking the commencement of the training phase. The training comprised five phases: an initial training session and a brief training phase preceding each trial. In the initial training, participants familiarized themselves with the process of assigning tasks to operators. They were granted the opportunity to request as many retries as needed until they felt adequately prepared to proceed to a trial. Before each experimental condition, participants were presented with the stress halo, and they engaged in a task assignment session, mirroring the initial training phase. This allowed them to understand how the stress halo evolved since the previous condition.

Task Assignment Trial

Throughout the experiment, participants were required to complete four trials within the virtual environment, involving the assignment of tasks to six virtual operators. The trials lacked a fixed duration; instead, participants were presented with 160 task artifacts distributed over 8 minutes (5 to 20 tasks every 30 seconds) for assignment to the operators. Trials concluded upon the successful assignment and completion of all tasks. The predetermined number of tasks (160) was established through preliminary pilot experiments, where the goal was to ensure that a sufficient number of tasks could induce a high-stress state among the virtual operators. While the number of tasks remained constant, the cubes representing the tasks generated to represent one of the four MATB-II tasks were following a uniform distribution. The variations among tasks were in name and duration, with two of the four task types taking twice as long to complete. It is important to note that operators exhibited no preferences or skill disparities among the task types; the time discrepancy in completion was solely dependent on the task type, with TRACK and RESMAN tasks taking twice the time as SYSMON and COMM tasks. Participants were asked to complete questionnaires (available as appendices) between each trial and after the experiment. The entire experiment lasted approximately one hour for each participant.

5.2.7 Results

A detailed analysis was conducted consistent with the analytical approach employed in the preceding study. The normality of the data distribution was initially assessed using the Shapiro-Wilk test for the parametric data. As none of the data (**Team score**,

Trial duration, and **Portion of time worked**) followed a normal distribution, for both parametric and non-parametric data, a dual analysis strategy was employed:

- Aggregating both conditions featuring 3 colours, a Wilcoxon signed-rank test was employed to compare them with the two remaining conditions involving 5 colours. This process was similarly applied to conditions with and without stress prediction.
- To investigate potential differences among conditions, Friedman χ^2 tests were conducted, followed by pairwise Wilcoxon signed-rank tests as post hoc analyses. A Bonferroni correction of the alpha value to 0.01 was applied for inter-condition comparisons

Again, when reporting results, the means will be presented followed by the standard deviation, the test statistics and the effect size.

Objective measures

A significant effect of the stress prediction on *Team Score* was found, participants achieved better performance with the *Prediction* conditions than with the *No Prediction* conditions (*Prediction score* = 138.3 ± 35.6 ; *No Prediction: score* = 129.2 ± 44.8 ; $W = 553.0$, $p = 0.046$, $r = -0.267$, see Figure 5.5), which supports **H1**. A significant effect of the number of colours on *Team Score* was found, participants achieved better performance with the 5 conditions than with the 3 conditions (5: *score* = 138.1 ± 40.2 ; 3: *score* = 129.3 ± 40.8 ; $W = 405.0$, $p = 0.001$, $r = -0.428$, see Figure 5.5), which supports **H2**. Further analysis showed that the 5~*Prediction* condition led to a significantly higher *Team Score* (*score* = 140.3 ± 38.4) than the 3~*No Prediction* condition (*score* = 122.4 ± 46.7 , $W = 91.0$, $p = 0.01$, $r = -0.49$), revealing a mutual reinforcement between the two factors.

A significant effect of the number of colours on the *Trial Duration* was found, participants completed trials faster with the 3 conditions than with the 5 conditions (3: *time* = 597.7 ± 75.4 ; 5: *time* = 620.0 ± 61.4 ; $W = 428.0$, $p = 0.003$, $r = -0.403$, see Figure 5.6). Further analysis showed that the 3~*No Prediction* condition led to a significantly lower *Trial Duration* (*time* = 581.3 ± 84.6) than the 5~*No Prediction* (*time* = 617.9 ± 60.0 , $W = 72.0$, $p = 0.002$, $r = -0.583$) and 5~*Prediction* conditions (*time* = 622.1 ± 63.8 , $W = 62.0$, $p = 0.001$, $r = -0.634$), confirming the results found in the first analysis.

A significant effect of the number of colours on the *Portion of time worked* was found, participants let the operators rest more with the 5 conditions than with the 3 conditions (5: *portion* = $50.30\% \pm 4.38\%$; 3: *portion* = $50.75\% \pm 5.67\%$; $W = 416.5$, $p = 0.008$,

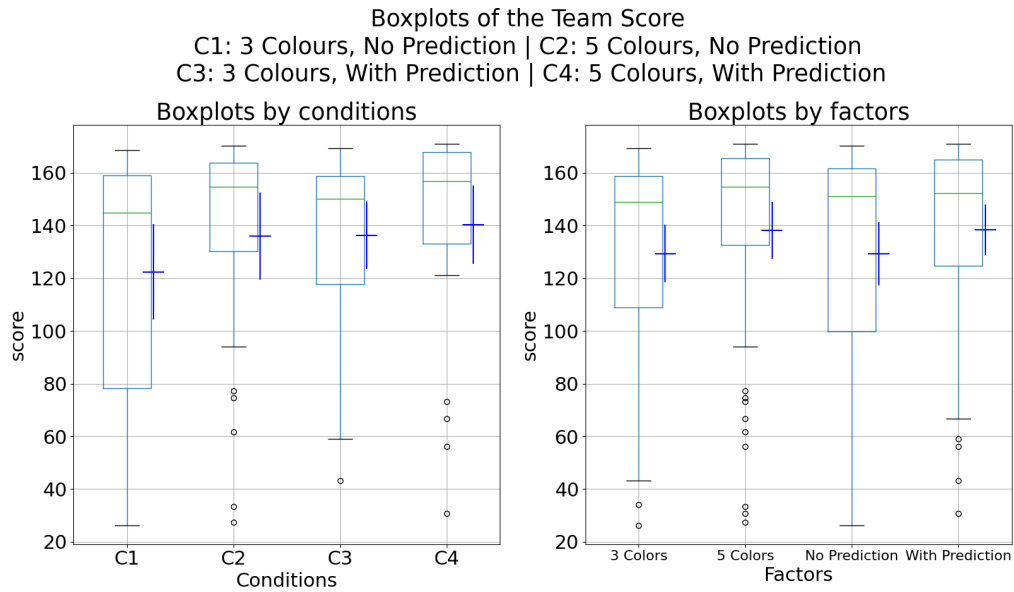


Figure 5.5 – Sum of all individual scores obtained by operators. The boxes in the figure represent the quartiles, with the median indicated by a green line. Additionally, blue horizontal lines depict the means, while blue vertical lines illustrate the corresponding confidence intervals.

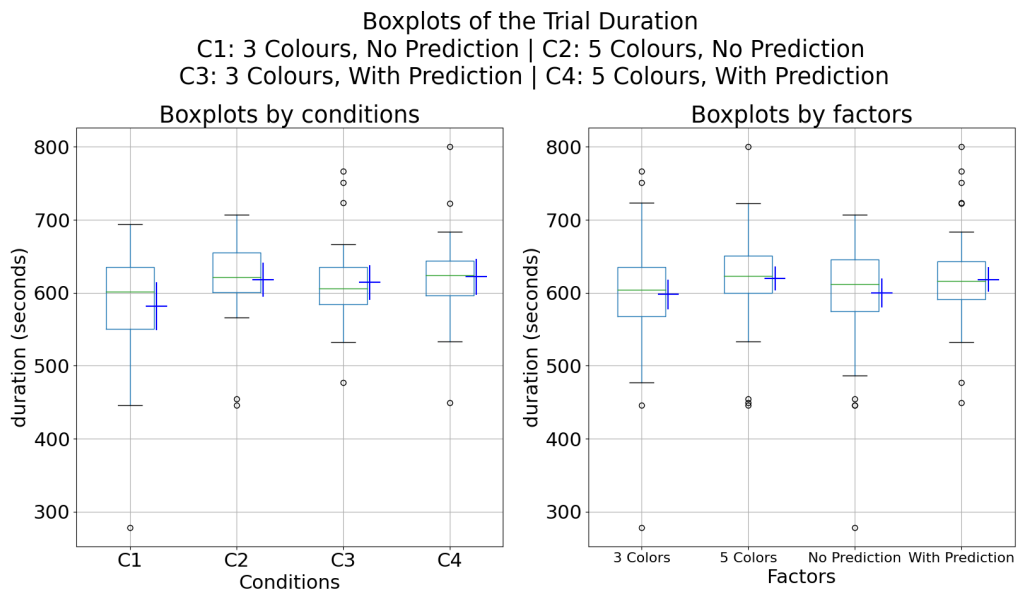


Figure 5.6 – Time (in seconds) trials lasted. The boxes in the figure represent the quartiles, with the median indicated by a green line. Additionally, blue horizontal lines depict the means, while blue vertical lines illustrate the corresponding confidence intervals.

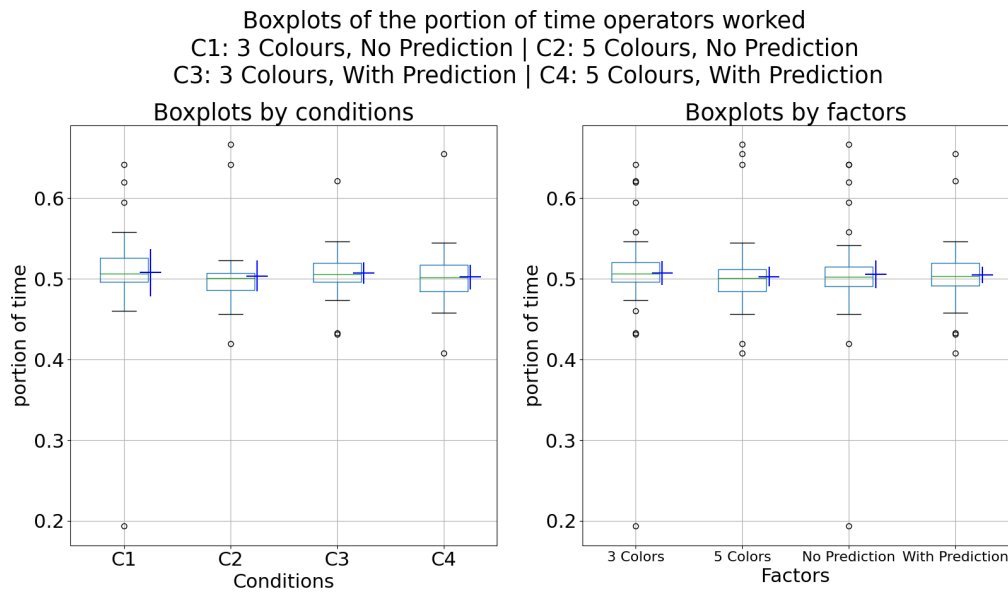


Figure 5.7 – Portion of time operators worked. The boxes in the figure represent the quartiles, with the median indicated by a green line. Additionally, blue horizontal lines depict the means, while blue vertical lines illustrate the corresponding confidence intervals.

$r = -0.354$, see Figures 5.7). This goes in the direction of **H2**, with a finer understanding of operators' inner status, participants let them rest more to reach a stress level closer to the optimal one.

Questionnaires

No significant difference was found between conditions when asking participants to state if the *task status* indicators helped them assign tasks ($help = 3.2 \pm 1.4$). On the other hand, a significant effect of the stress prediction was found on the same evaluation of the **Current Stress**, participants considered this feedback less useful when they had stress prediction (*No prediction: help* = 4.5 ± 0.7 ; *Prediction: help* = 3.9 ± 1.2 ; $W = 109.5$, $p = 0.005$, $r = -0.375$, see Figure 5.8). For the stress prediction components, the **Future Stress** and **Tested Future Stress**, the number of colours did not have any effect on the participants' reported helpfulness of the components.

In reviewing the overall NASA-TLX score, no significant difference was found. However, a detailed questionnaire assessment revealed that participants experienced significantly different levels of mental demand, effort, and frustration across the various conditions.

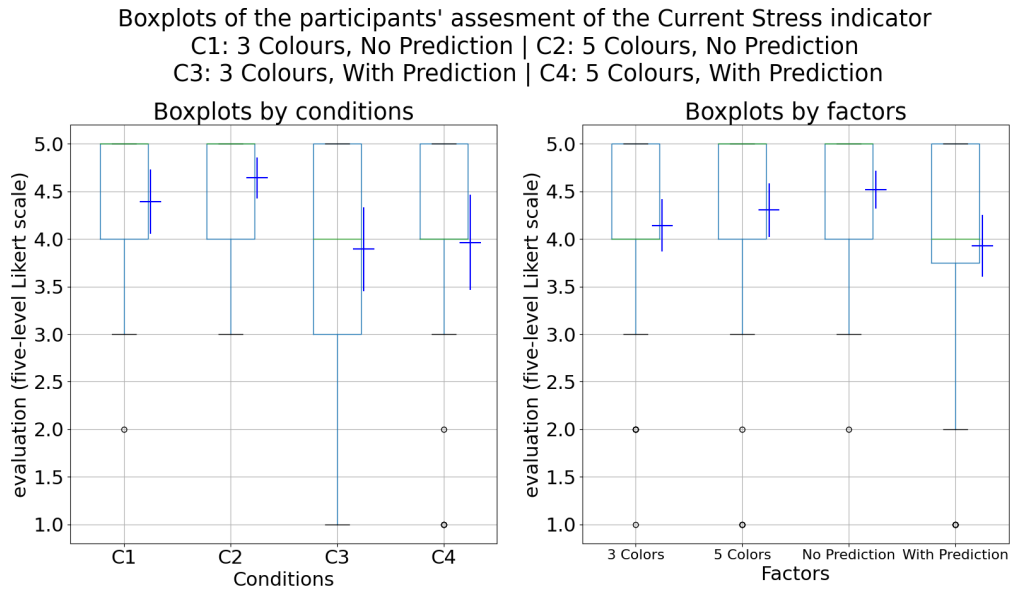


Figure 5.8 – Participants' assessment of the utility of the Current Stress indicator. The boxes in the figure represent the quartiles, with the median indicated by a green line. Additionally, blue horizontal lines depict the means, while blue vertical lines illustrate the corresponding confidence intervals.

A significant effect was found for both factors on the mental demand (see Figure 5.9), participants felt the task more mentally demanding with three colours ($3: mental = 3.16 \pm 0.95$; $5: mental = 2.89 \pm 1.0$; $W = 78.0$, $p = 0.03$, $r = -0.288$), and without stress prediction ($No Prediction: mental = 3.16 \pm 0.95$; $Prediction: mental = 2.89 \pm 1.0$; $W = 150.0$, $p = 0.038$, $r = -0.277$). From the participants' perspective, the $3 \sim No Prediction$ condition put a higher mental demand on them ($mental = 3.39 \pm 0.92$) than the $5 \sim Prediction$ ($mental = 2.86 \pm 1.08$, $W = 22.5$, $p = 0.006$, $r = -0.517$) and the $3 \sim Prediction$ ($mental = 2.93 \pm 0.94$, $W = 12.0$, $p = 0.007$, $r = -0.468$) conditions.

The number of colours significantly affected the effort when no stress prediction was provided (see Figure 5.10): participants felt the task required more effort with three colours ($3 \sim No Prediction: effort = 3.14 \pm 0.89$; $5 \sim No Prediction: effort = 2.54 \pm 0.92$; $W = 10.0$, $p = 0.006$, $r = -0.52$).

The stress prediction significantly affected the frustration (see Figure 5.11): participants felt more frustrated without the stress prediction ($No prediction: frustration = 2.04 \pm 1.0$; $Prediction: frustration = 1.73 \pm 0.90$; $W = 66.5$, $p = 0.01$, $r = -0.336$).

A significant effect of the number of colours on the estimation of the operators' speed

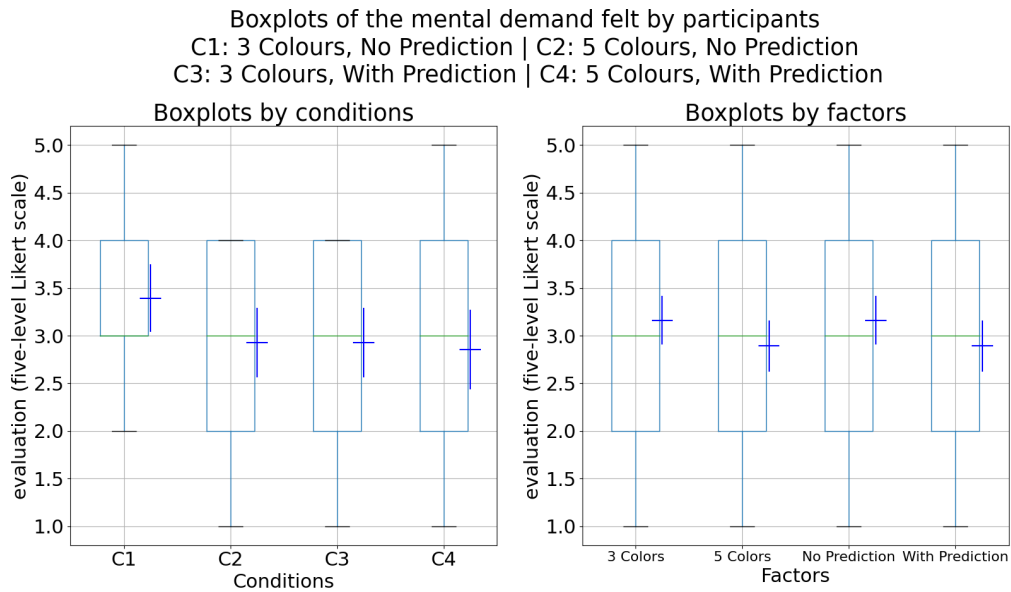


Figure 5.9 – Mental Demand measure of the NASA Task Load Index questionnaire. The boxes in the figure represent the quartiles, with the median indicated by a green line. Additionally, blue horizontal lines depict the means, while blue vertical lines illustrate the corresponding confidence intervals.

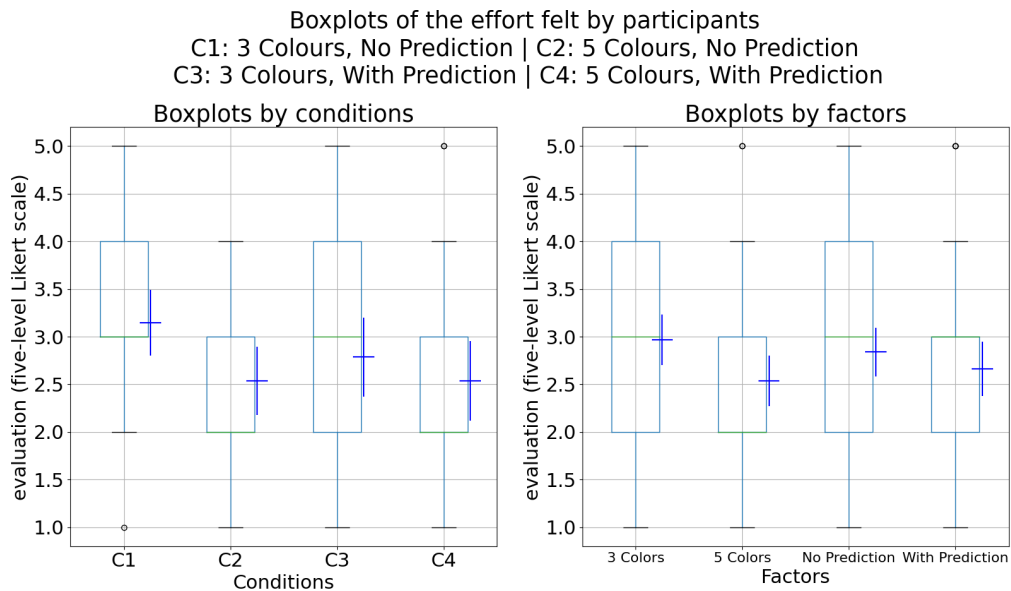


Figure 5.10 – Effort measure of the NASA Task Load Index questionnaire. The boxes in the figure represent the quartiles, with the median indicated by a green line. Additionally, blue horizontal lines depict the means, while blue vertical lines illustrate the corresponding confidence intervals.

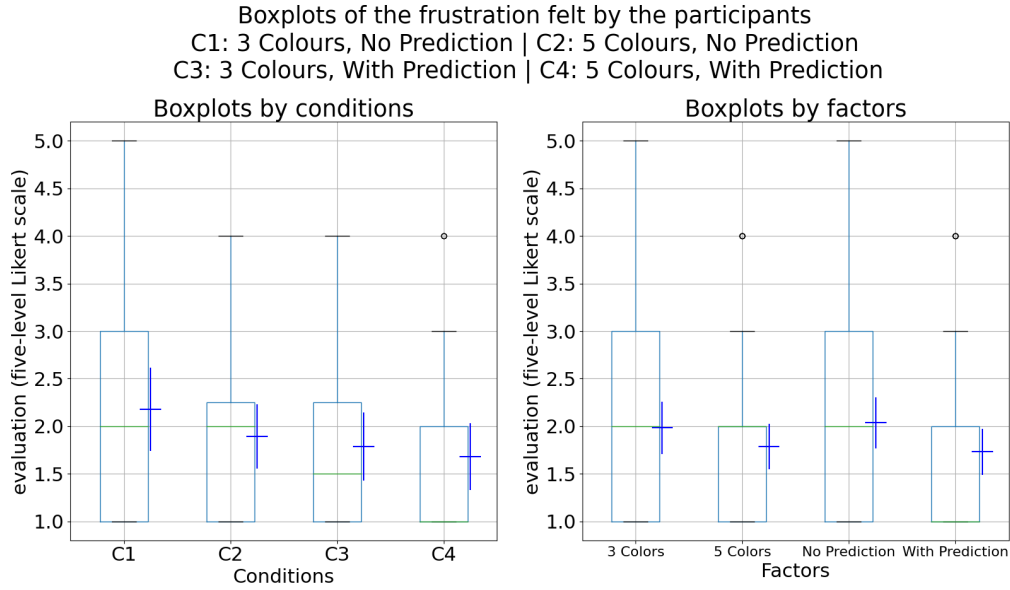


Figure 5.11 – Frustration measure of the NASA Task Load Index questionnaire. The boxes in the figure represent the quartiles, with the median indicated by a green line. Additionally, blue horizontal lines depict the means, while blue vertical lines illustrate the corresponding confidence intervals.

was found, participants felt more confident identifying slow and fast operators with the 5 conditions than with the 3 conditions ($5: identification = 3.23 \pm 1.1$; $3: identification = 2.91 \pm 1.25$; $W = 165.0$, $p = 0.03$, $r = -0.292$, see Figure 5.12).

At the end of the experiment, when asked how many colours they preferred having during the experiment, 5 participants preferred having 3 colours and 23 participants preferred having 5 ($\chi^2 p = 0.00067$).

Approach	1	2	3	4	5
<i>3~No Prediction</i>	9	13	5	8	
<i>5~No Prediction</i>	8	16	7	5	
<i>3~Prediction</i>	5	11	2	3	17
<i>5~Prediction</i>	6	10	4	4	17

Table 5.1 – Participants' reported strategy.

Throughout the experiment, participants reported their strategy after each condition, see Table 5.1. Five primary approaches emerged from their reports:

- 1 *Assign easy tasks to most stressed operators and hard tasks to least stressed ones*
- 2 *Wait for the operators to reach a lower level of stress before assigning tasks to them*

Boxplots of the participants' assesment of their ability to identify slow and fast operators
 C1: 3 Colours, No Prediction | C2: 5 Colours, No Prediction
 C3: 3 Colours, With Prediction | C4: 5 Colours, With Prediction

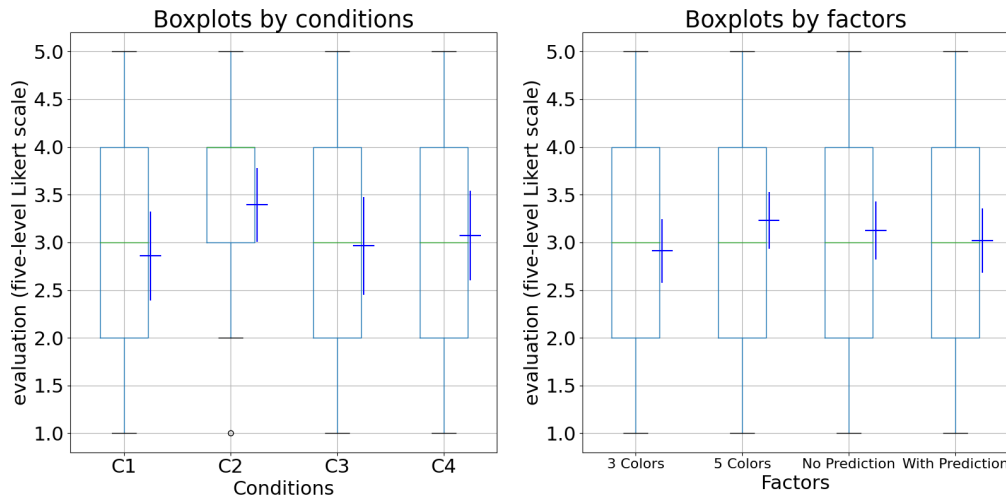


Figure 5.12 – Participants' ability to identify slow and fast operators The boxes in the figure represent the quartiles, with the median indicated by a green line. Additionally, blue horizontal lines depict the means, while blue vertical lines illustrate the corresponding confidence intervals.

3 *Assign multiple tasks at once*

4 *Assign hard tasks to fastest operators*

5 *Assign tasks only if the prediction of operators' stress is not too high*

While the tendencies of adopting Approaches 1 to 4 are similar regarding the conditions, most participants reported having the stress prediction indicators at the centre of their focus when available. Twenty participants adapted their strategies based on visual changes in stress feedback, 16 of them did so because of the presence of stress prediction and 2 did so because of the change in the number of colours. Eight participants who reported not changing their strategy explained that they kept the same baseline throughout the whole experiment: not assigning multiple tasks at once to the same operator and keeping them at a low level of stress. Participant 3 stated that the absence of time limitation encouraged the adoption of this strategy, whereas Participant 10 explained that without fundamentally changing, it becomes more efficient with stress prediction and more levels of stress. Regardless of the stress feedback changes, 9 Participants changed their strategy throughout the experiment, 3 to focus more on the operators' speed, and 5 to keep the operators' stress lower and thus improve their performance.

All participants answered that the current stress feedback was important, 2 reported this feedback helped them to maximise the team score, 4 reported it helped them to plan break times for the operators, and 1 reported using it to choose between assigning a hard or easy task. While agreeing on the importance of having feedback on the stress level of operators, 7 participants argued its efficiency, 4 among them justified this doubt by explaining that when the future and tested stress were available the current stress became useless. Indeed, those participants reported that having both current and future stress brought confusion and the prediction alone would have been enough to "safely assign tasks" (P20).

Twenty-three participants recognize the importance of feedback on future stress levels in aiding strategic planning and task assignment. Eight participants reported that having a prediction of the future stress of operators gives a better vision to plan the task assignment. Specifically, 2 participants mentioned it aided in timing task assignments, while 5 participants noted its usefulness in selecting which operator should be assigned a task. Additionally, 2 participants reported its assistance in determining the type (easy or difficult) of task to assign. It also helps to avoid situations where operators would reach higher levels of stress. However, 5 participants disagreed and either reported that the Tested stress was more relevant and reliable than the Future stress to refine their strategy (P6, P22 & P27), or that the Future stress was out of their consideration when assigning tasks (P12¹ & P13).

Overall, 24 participants recognize the significance of incorporating tested future stress feedback into the decision-making framework for task management. Fourteen of them reported that the tested future stress brought them confidence in reaching a good performance in their decision-making process, and 3 other participants stated that this indicator helped keep all operators at low levels of stress. Participants disagreeing justified their answer by either explaining that they preferred to focus on the Current and Future stress feedback instead (P3, P5, P10 & P26), or that the Tested stress was out of their consideration when assigning tasks (P12¹). P5 completed their answer by explaining the tested future stress considered the two held tasks but as they used to assign tasks to multiple operators at once, the tested future stress was thus not reflecting the right estimation.

1. P12 scored the lowest of all participants, over the 4 trials, they got team scores between 30 and 43 over the 172 points available.

5.2.8 Discussion

In addressing **RQ2.3** and **RQ3.1**, this chapter presents a contribution following the trajectory established in the previous study. It introduces a novel visualization technique designed for team leaders to effectively convey the current and future stress levels of team members, aiding in the strategic allocation of tasks and it relates a comprehensive study to assess the efficiency of the proposed visualization technique for team leaders.

Study outcomes

Validating **H1**, the results demonstrate a significant enhancement in team performance when team leaders are provided with a prediction of their team members' evolving *inner status*. Participant feedback indicates that this prediction holds greater relevance than sharing the current *inner status*, offering a better idea of workers' well-being over time. Moreover, the predictive information eases the mental demand and frustration experienced by team leaders during task assignments. The participants' reports explain that stress prediction is part of the task assignment job and having feedback on such a prediction eases the whole task assignment process, P27 stated that “*depending [solely] on the current stress required a bit more guesswork to figure out when to assign tasks*”. Furthermore, not considering the Future and Tested stress feedback when assigning tasks seems to lead to poor team performance, as observed with P12 who clearly stated not using either prediction indicator being the participant who scored the lowest. These findings suggest that studying the provision of estimated future *inner status*, even without the current *inner status*, represents a promising research direction.

Since predicting the evolution of workers' *inner status* enhances team performance, the key inquiry is the optimal precision level of such feedback for maximal improvement. The findings demonstrated that discretizing the continuous value representing *inner status* into 5 levels led to better team performance than with only 3 levels, thereby validating H2. Having 5 levels of *inner status* enabled team leaders to keep their workers' *inner status* closer to the optimal level, letting them rest more, and resulting in better team performance, which can explain the longer trials in these conditions. As for the stress prediction, presenting this information with 5 levels created lower mental demand on team leaders. In addition to explicitly expressing a preference for the 5-level presentation of *inner status* over the 3-level counterpart, participants felt more confident in identifying their team members' work speed with that 5-level presentation.

Considering both factors, the *inner status* prediction and the abstraction level, the peak performance was achieved when offering a prediction of future *inner status* and presenting it with five abstraction levels. On the opposite, not providing an *inner status* prediction with only three abstraction levels leads to higher mental demand and effort for the team leader.

Participants' overall feedback on the experiment highlighted various perspectives. These diverse perspectives offer valuable insights into participants' experiences and suggestions for refining the experiment's design. For example, P4 appreciated the incorporation of five stress levels but felt overwhelmed by the resulting complexity. This sentiment was echoed by P16, who proposed an alternative approach, suggesting the use of five distinct colours instead of the hatched texture to represent intermediary stress levels. While exploring this option during the development of the stress halo, considerations for accessibility, particularly for colourblind individuals, led to the decision to maintain only three colours with high contrast. However, future investigations could explore alternative methods for distinguishing the five stress levels, aiming to ensure that the stress halo remains comprehensible for colourblind individuals while minimizing confusion associated with the hatched texture. This might involve incorporating symbols and/or numerical values into the indicator. Beyond the scope of this specific study, P6, who was also involved in the preceding study detailed in Chapter 4, expressed the utility of incorporating a history of operators' stress levels. They recommended considering both the stress history and the stress halo for presentation to team leaders when implementing feedback on workers' *inner status* in real-world scenarios.

These observations suggest that collaborative setting designers provide an estimation of the evolution of the *inner status* of workers to team leaders, accompanying the current *inner status* feedback if not alone. In that process, a precise yet intelligible abstraction has to be considered. Indeed, abstracting the *inner status* continuous value to five levels leads to better performance being more precise. Pursuing research on sharing people's status should investigate further for the optimal abstraction level of presented information, and exhaustively identifying the factors affecting it.

Limitations

In line with standard scientific practice, this study is subject to some limitations. Notably, it refrained from imposing time constraints on participants, aiming to facilitate the inclusion of individuals with limited experience, given only basic training for the

assigned tasks. As time was not a constraint, the 5 participants who reported changing their strategy unrelated to the stress feedback changes realised that they could give more rest time to the operators, P8 stated: “*you really have to take time for your operators to rest*”. Furthermore, the study investigated the impact of various feedback mechanisms provided to a team leader within a virtual team environment, where team members were simulated. This simulation introduces a degree of separation between the study’s outcomes and their direct applicability to real-world scenarios.

To delve deeper into the effects of abstraction levels and the presence of stress prediction on trial duration, future research could involve individuals with managerial backgrounds, placing a stronger emphasis on the practical implications in professional settings. To mitigate the limitations inherent in the current study, a crucial next step would entail conducting experiments with human workers. This would involve incorporating physiological sensors to precisely measure stress levels and deploying the visualizations in authentic contexts, be it industrial, military, medical, or otherwise.

5.3 Conclusion

This chapter shows that providing team members’ inner status predictions to their team leader improves team performance in a simulated team. Presenting this prediction with a slighter abstraction, i.e. with more discrete levels, led to the best performance in the experimental context and was preferred by users. In the continuity of the previous study, this shows how team management could evolve to achieve better team performance and members’ well-being. Again, providing users’ status to team leaders should be highly considered in works where team members must perform their tasks reliably with little to no mistakes. This time, however, the study outcomes suggest that providing an estimation of the status evolution is both appreciated by the team leaders and a source of better team performance. As participants reported, the prediction is even more useful for the task assignment job than having feedback on the current team members’ status. For future team members’ *inner status* feedback provided to team leaders, the information should thus contain an estimation of the future stress level of the team members who could potentially receive workload.

As with the preceding study, the implications of this research transcend the boundaries of the simulated team environment, offering applications across various industries. In these contexts, incorporating feedback on users’ inner status and an estimation of its evolution

for team leaders holds the potential to enhance team performance and contribute to the overall well-being of team members. This paradigm shift towards a more empathic approach to teamwork may prove valuable in industries where reliable task performance with minimal errors is essential. Although the study concentrated on colocated teams, the insights obtained apply to diverse teamwork scenarios, including remote collaborations facilitated through XR shared workspaces. The potential applications of these findings will encounter similar challenges in practical implementation. Additionally, factors such as tailoring feedback mechanisms to specific industry needs, addressing potential resistance to change, and integrating these techniques into existing workflows should be taken into account. Further research and collaboration with industry professionals can yield valuable insights into overcoming these challenges and optimizing the application of our findings in real-world work settings.

CONCLUSION

This PhD dissertation explored how to enhance people’s awareness of collaboration with Extended Reality (XR). This last chapter will synthesize the contributions discussed in the dissertation before proposing future work to pursue the investigations. The last section will open the outcomes of the presented work to larger perspectives.

Contributions and Outcomes

In this dissertation, I addressed the limitations identified in the literature review concerning awareness of collaboration, particularly regarding the presentation of available status data and the enhancement of mutual understanding. The investigation explored methods for sharing status information among team members and their leaders to improve collaborative outcomes. This endeavour unfolds through three progressive acts, each building upon the foundation laid by its predecessor.

The first act investigated the impact of **sharing status** among equal-level workers on awareness of collaboration. On a larger scale, the second act retraced the investigations of **sharing team members’ status with their leader** to improve their task allocation process. The third act proposed to present **team members’ predicted status** to their leaders to further improve their task allocation process. Thus, this dissertation contributes methodologically and experimentally to the design of future XR workspaces with enhanced awareness of collaboration.

The first contribution has been to improve workers’ awareness of their homologous pursuing the objective of increasing mutual understanding and ability to help each other. This first investigation focused on symmetric and synchronous collaboration to study the impact of sharing each one’s status in a small collaborative setting. I thus proposed several indicators of a collaborator’s status, whether for identification purposes or for sharing *task status* and inner status. These indicators give information on both past and current values of the system or of the well-being of the collaborator. Although both

task status and inner status indicators were proposed, the experiment I conducted with twenty participants focused on evaluating the impact of *task status* on performance and mutual help effectiveness and occurrence. With this user study, I demonstrated that giving information about the *task status* enhances the detection of the need for help and that people prefer instantaneous information to a progression history in such collaborative contexts. Sharing such task status indicators among team members thus proves to be relevant to improving the awareness of collaboration among team members in symmetric and synchronous collaboration. Building upon this finding, the next step would be to assess their effectiveness in different collaborative contexts, which was explored in the subsequent investigations.

Exploring collaboration on a larger scale, the second contribution improved the collaborative outcomes by providing team leaders with feedback on their members' status. In context requiring a team leader to monitor workers, efficient collaboration requires not only perceiving partners' positions and actions but also understanding their status (task activity, emotional states, fatigue, etc.), which is even more crucial to team leaders when assigning work to their team members. The process of assigning tasks to a working team was thus enhanced with feedback on members' *task status* and well-being information. For the *task status*, I proposed indicators on the past, present and future states of the tasks assigned to each worker, and for the *inner status* of a worker, I proposed another indicator of a single well-being measure labelled as 'stress' for the general public comprehension. All indicators were implemented with two presentation modes: *Literal* displaying information as raw as possible with written words and numbers; and *Symbolic* with abstractions such as icons, graphs or 3D artifacts. An experiment conducted with twenty-four participants evaluated the relevance of each indicator and their effectiveness in improving collaborative outcomes. This study revealed that a non-abstracted presentation of *inner status* leads to better team performance, even if people preferred a presentation with symbols abstracting data. Furthermore, this contribution highlights the significance of sharing inner status information among team members, particularly in the context of monitoring a team of workers. However, since both *Literal* and *Symbolic* presentations offer distinct advantages, and some indicators perform better with one or the other, further research is required to determine the optimal abstraction level for each status indicator.

Refining the outcomes of the previous contribution, I further investigated the presentation of the *inner status*. As the outcomes of the two previous contributions suggested, providing current and future status information was worth exploring more deeply. As

related work shows that predicting *inner status* evolution is possible although being complex [93], this contribution explores the impact of presenting such prediction to team leaders on collaborative outcomes. I thus proposed to provide team leaders with a prediction of their workers' *inner status* after completing all their assigned tasks. This prediction was presented through a floating halo placed around the head of a worker with the inner status level shown by colours. To evaluate this proposition, I experimented with twenty-eight participants in search of the impact of such prediction on collaborative outcomes and to initiate research for the best abstraction level of the proposed indicators. The results of this experiment showed that presenting this prediction with a slighter abstraction, i.e. with more discrete levels, leads to even better performance and is preferred by people being presented with it. Furthermore, participants indicated a preference for receiving predictions of their team members' status evolution compared to current status feedback, highlighting the potential value of this approach in facilitating effective teamwork. This contribution advances the investigation into the relevance of sharing status information and explores the optimal abstraction level to facilitate efficient teamwork while minimizing confusion for team leaders.

Last, for experimental purposes, I developed an open-source platform, available at https://github.com/ThomasRinnert/MATB-II_CollabVR, to facilitate collaboration within XR workspaces. As this platform offers high customizability, it served as a valuable tool for validating my propositions through experimentation. Additionally, this extensible tool holds significant potential for future research. Excluding pilot studies, three experiments were conducted using this platform to investigate collaboration within XR environments:

- A user study on sharing user status during synchronous collaboration (see in Chapter 3),
- A user study on monitoring team members' status for task allocation (see in Chapter 4), and
- A user study on monitoring a prediction of team members' evolution of their inner status for task allocation (see in Chapter 5).

Future Work

The roadmap for future research unfolds across various temporal horizons, offering opportunities for short-term, medium-term, and long-term investigations. Each time frame presents distinct challenges and objectives, shaping the potential trajectory of research

endeavours.

In the short term, there are several opportunities to enhance the outcomes of the research outlined in this dissertation. For instance, a short project could focus on the integration of various sensor data, replacing the current simulated data with authentic physiological data. This endeavour would lay the groundwork for deploying real-time studies on collaboration within actual teams. Additionally, an investigation leveraging Artificial Intelligence (AI) and Machine Learning (ML) algorithms to interpret and analyze the inner status of team members could be undertaken, also contributing to such deployment. Furthermore, a project exploring the interaction dynamics between team leaders and the awareness cues could be conducted. This initiative would delve into aspects such as resizing and organizing indicators, as well as implementing alerts to capture the leader's attention on specific issues.

In the medium term, opportunities exist to further develop the concepts outlined in this dissertation. This could involve proposing enhanced awareness indicators or refining the operator model to enable more realistic experimentations within a simulated environment. Additionally, engineering efforts to extend the experimental platform introduced in this dissertation could facilitate the exploration of more complex collaborative scenarios, such as integrating multiple MATB-II systems and interfaces for team interaction. Another potential project could focus on studying team monitoring using inner status prediction alone, starting to address privacy concerns by eliminating feedback on current status. Furthermore, investigations into the optimal ergonomic design of indicators could be conducted to propose effective awareness cues. Such future work holds the potential to apply research outcomes to practical use cases, including collaborations with industrial partners.

In the long term, there are opportunities to further advance the research presented in this dissertation, particularly regarding the optimal abstraction level of status information. The current work suggests that simplistic approaches, such as abstracting continuous values to discrete levels, may not be the most effective for improving team performance. Therefore, investigating the most intelligible abstraction levels for each dimension of user status remains a worthy exploration. Furthermore, while this dissertation primarily focuses on visual feedback, there is a need to explore multimodal approaches for conveying information. Future research could investigate incorporating additional modalities into awareness cues and identifying the most relevant ones for conveying collaboration awareness. However, such research must consider the highly context-dependent nature of

modalities, such as the limited effectiveness of the audio modality in noisy environments. Collaboration with end users, including industrial partners, could provide valuable insights for guiding these endeavours. Investigations could also address technical challenges such as facilitating large groups of users sharing the same XR workspace, as seen in events like virtual conferences or VR Massive Multiplayer Online games. Additionally, research could delve into complex group dynamics, exploring scenarios with multiple non-exclusive roles involved. Again, collaborations with industries such as Defense, Health, or other sectors with clearly defined roles could provide valuable contexts for studying this topic. Such partnerships would enable the direct application of research outcomes to real-world scenarios, with potential implications for enhancing teamwork effectiveness.

Perspectives

While the dissertation primarily focused on colocated teams, the insights gained are transferable to various teamwork scenarios, including remote collaborations facilitated through XR technologies. For example, the experimental platform developed for this research was utilized in a demonstration involving collaboration between Australian and French participants. However, it is important to acknowledge an unavoidable limitation: the speed of light and network introduce a latency between users in France and Australia. Although this latency was not prohibitive in the applicative contexts discussed in the dissertation, it may warrant consideration in highly time-critical co-manipulation tasks.

The implications of these investigations extend beyond symmetric collaboration and simulated teams, prompting considerations for implementation in various industries. The application of different presentations of status information and strategies for team coping, as identified in this research, has the potential to reshape team management practices. However, it is essential to acknowledge the implications of deploying such technology in real-world scenarios, including ethical concerns surrounding the sharing of private data, the risk of managerial pressure leading to employee burnout, and the cognitive load resulting from changes in working habits.

Like any powerful tool, the implementation of feedback on users' inner status and strategies for team coping must be approached thoughtfully and ethically to avoid potential misuse. It is important to recognize that there are no universal solutions; rather, it is the responsible and informed application of these insights that will drive positive outcomes in real-world work settings. Indeed, implementing feedback on users' inner status

for team leaders could enhance team performance and contribute to the overall well-being of team members. This implies a shift towards a more empathic teamwork approach that may prove valuable in industries where reliable task performance with minimal errors is crucial. Although, we recognize that the practical implementation of these techniques comes with its challenges.

Of course, as soon as real people are implied in such settings, ethical problems will have to be addressed. Sharing user status must follow privacy rules and ethics and must require the consent of monitored subjects. As participants in the experimentations reported, the prediction of users' inner status is even more useful for the task assignment job than having feedback on the current team members' status. This could be the beginning of a solution when addressing the ethical issue of sharing people's status, with the future inner status estimation implicitly integrated into an algorithm advising team leaders on task allocation, without explicitly disclosing specific details about the workers' status. If a system only provides a prediction of people's status when they are at risk, for their own sake to not put them under more pressure, this system would be less intrusive than what is currently proposed in the literature and deployed in industry.

Moreover, factors such as adapting the feedback mechanisms to specific industry needs, addressing potential resistance to change, and integrating these techniques into existing workflows should be considered. Further research and collaboration with industry professionals can provide valuable insights into overcoming these challenges and optimizing the application of my dissertation's contributions in real-world work settings.

Eventually, it is essential to recognize that teamwork extends beyond human interaction alone. With the increasing integration of technology into work environments, teams often consist of both humans and machines collaborating together [69]. While machines may not possess the same nuanced status measures as humans, equivalent metrics can be devised and explored. For instance, mechanical stress can be considered analogous to the physical strain experienced by humans, while monitoring energy levels in a battery could mirror human fatigue. This broader perspective underscores the need for adaptable frameworks encompassing both human and machine elements within collaborative settings.

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Chapter 3

The first appendix is the presentation of the original MATB-II design, followed by a document presenting the unexplored design for the collaborative VR adaptation. The four following documents are the ethics committee approval, the participant information sheet, the guide for interacting within the virtual environment, the consent form and the end-of-experiment questionnaire used in the study presented in Chapter 3.

MATB-II original design

The MATB-II is a desktop application (see Figure 6.7) composed of six components, each of which is referred to by abbreviations: SYSMON for the system monitoring task, TRACK for the tracking task, COMM for the communication task, RESMAN for the resource management task, WRS for the workload rating scale, and SCHED for the scheduling of the COMM and TRACK tasks. The application triggers events by reading a scenario and the subject has to respond to them as fast and accurately as possible.

“The Multi-Attribute Task Battery (MATB-II) is a computer-based task designed to evaluate operator performance and workload. MATB provides a benchmark set of tasks analogous to activities that aircraft crew members perform in flight, with freedom to use by non-pilot subjects. The MATB requires the simultaneous performance of monitoring, dynamic resource management, and tracking tasks. The simultaneous performance of multiple tasks is a central feature of the MATB and it is this feature that is consistent with most operational systems and thus makes the task useful for our purposes as a research platform. The Multi-Attribute Task Battery (MAT Battery) was originally developed in the early 1990’s at LaRC (Comstock & Arnegard, 1992) and re-implemented under Microsoft Visual Studio.NET (VS.NET).”

– NASA (<https://matb.larc.nasa.gov/>)

The SYSMON task requires the subject to check that two warning lights and four scales stay in their normal state. Among the warning lights, one green is normally on and the other is red and normally off, lights are grey when they are off. The subject has to switch back the green light on when it turns down and conversely, switch off the red light if it turns on. The four scales are moving up and down around the middle, the subject has to spot when a scale shifts its position away from the middle. This task allows the measure of the time between an event (a light switch or a scale shifting away from the centre) and the subject reaction. In the desktop application, to react and complete the task, the subject can either use a mouse pointer to click on the monitored element quitting its normal state or press a linked button on a keyboard.

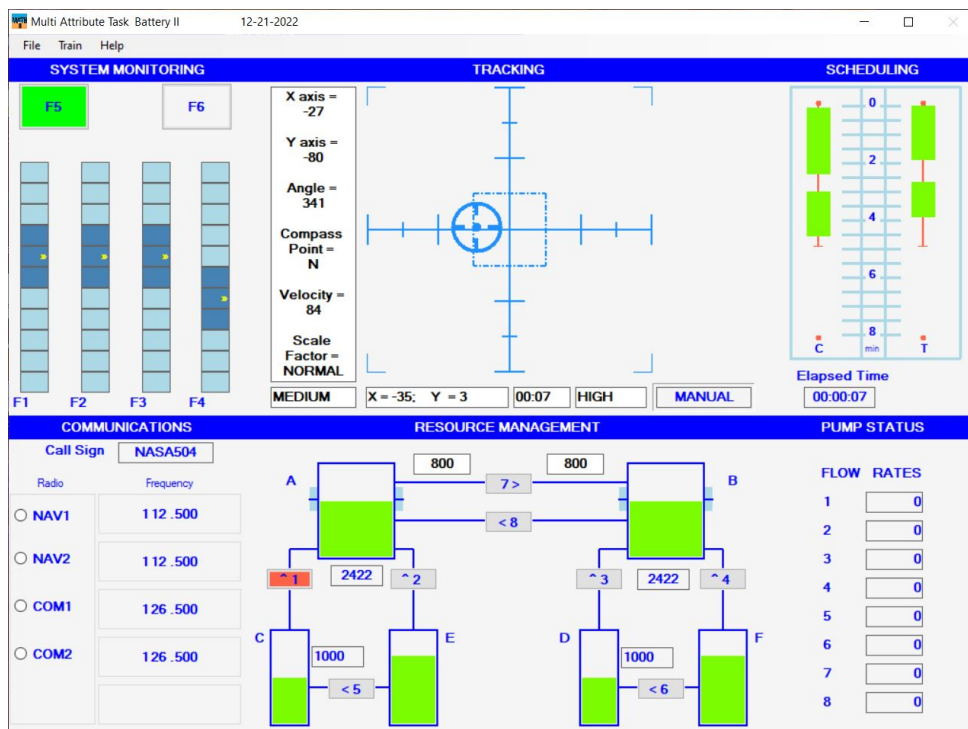


Figure 6.1 – NASA Multi-Attribute Task Battery II (MATB-II) original desktop computer interface. The subject has to operate the SYSMON task in the upper left corner of the interface, the COMM task in the lower left corner, the TRACK task in the upper middle, and the RESMAN task in the lower right corner. The scheduling of incoming COMM and TRACK tasks is shown in the upper right corner of the interface.

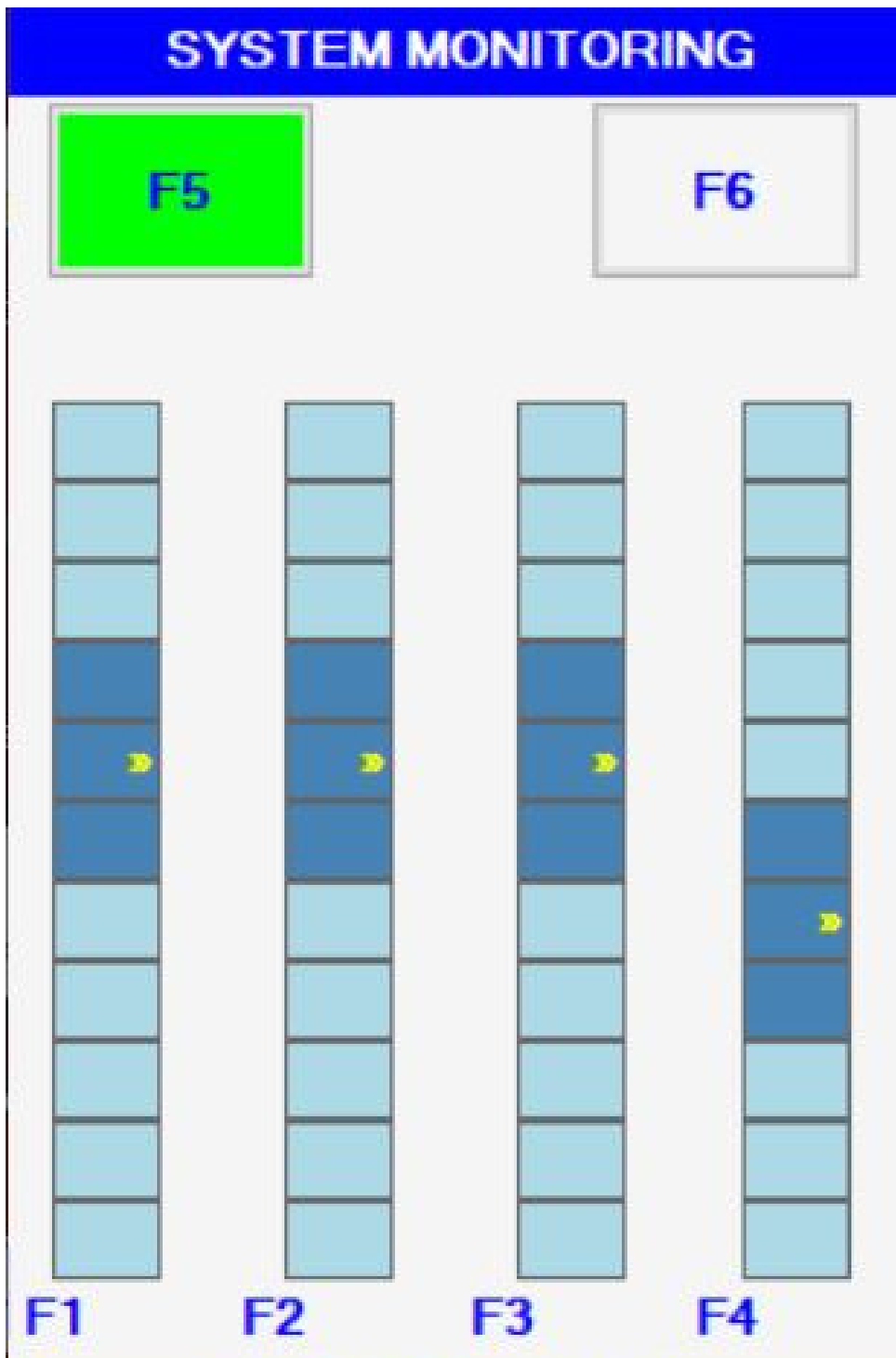


Figure 6.2 – NASA Multi-Attribute Task Battery II (MATB-II), SYSMON interface.

The COMM starts by playing a pre-recorded instruction to change the frequency of one of four radios. The instruction begins by repeating a call sign twice and then asks to tune a specific radio to a new frequency. Not all incoming messages address the user, having NASA-504 as a call sign, for decoys another call sign is used, and the message has to be ignored. This task allows the measure of both the time between an instruction and the subject reaction and the responses to instructions revealing if the subject made the right modifications or the amount of error they made. In the desktop application, to react and complete the task, the subject uses a mouse pointer to click on a radio to select it and either click on the arrow buttons or use buttons on a keyboard to tune the frequency. To confirm the modification, the subject has to click on the "Apply" button or press a button on a keyboard.

When activated, the TRACK task requires the subject to maintain a target at the centre of a frame. The target position continuously fluctuates and has abrupt changes at regular time intervals. The tracking system has two modes, "AUTOMATIC" and "MANUAL", the former keeps the target at the centre of the frame with no action from the subject and the latter requires the subject to use a joystick to guide the target back to the centre and keep it there until the task switch back to the "AUTOMATIC" mode. The performance of this task is measured by the amount of time the target stayed in the inner frame.

Like the SYSMON task, the RESMAN task is always active. It requires the subject to balance the fuel in a hydraulic system to keep two tanks around an ideal level, those tanks represent the fictional aircraft fuel reserves. To do so, the subject can turn on or off any number of the eight pumps to move fuel from the infinite sources (tanks E and F) to the fuel reserves (tanks A and B) directly or via buffers (tanks C and D). Pump failures can occur and are shown by a red light on the failed pump that gets repaired after some time. The record of the pumps' state and tank levels allows the measure of the amount of time the fuel reserves stayed at the ideal level.

The WRS is based on the NASA task load index (NASA-TLX [68]) where the subject has to rate their resented workload on 6 dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration. While the subject fills the form in a separate window or via another way (eg. a paper version of the NASA-TLX), the simulation is paused.

The SCHED component displays a timeline of the upcoming COMM and TRACK activations over the next eight minutes. The COMM and TRACK tasks are represented on the timeline by green blocks on top of a red line starting at the beginning of the scenario

COMMUNICATIONS	
Call Sign	NASA504
Radio	Frequency
<input type="radio"/> NAV1	1 12 .500
<input type="radio"/> NAV2	1 12 .500
<input type="radio"/> COM1	1 26 .500
<input type="radio"/> COM2	1 26 .500

Figure 6.3 – NASA Multi-Attribute Task Battery II (MATB-II), COMM interface.

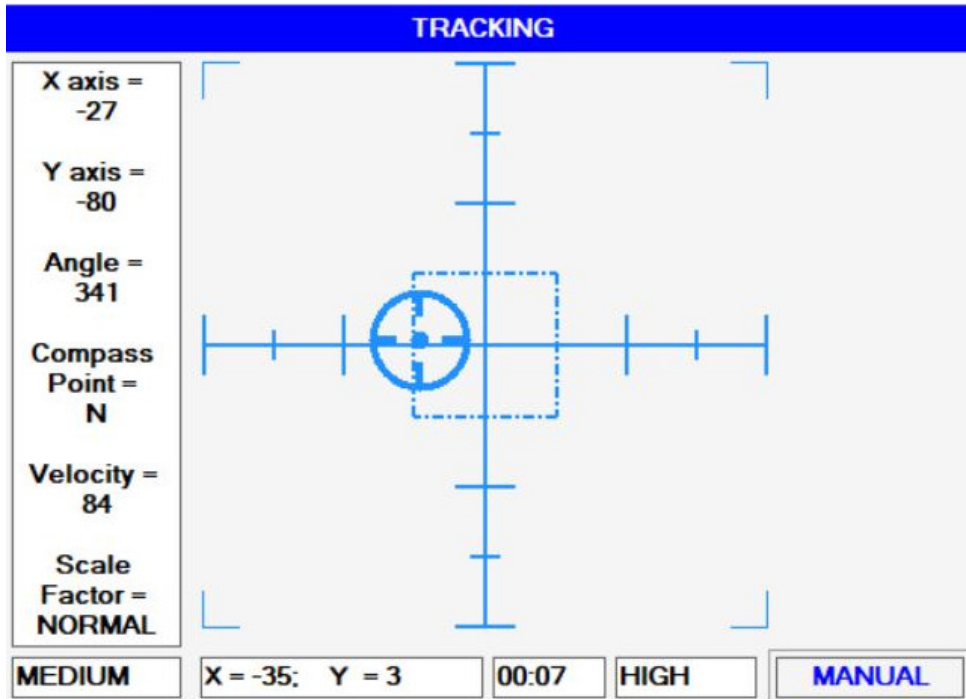


Figure 6.4 – NASA Multi-Attribute Task Battery II (MATB-II), TRACK interface.

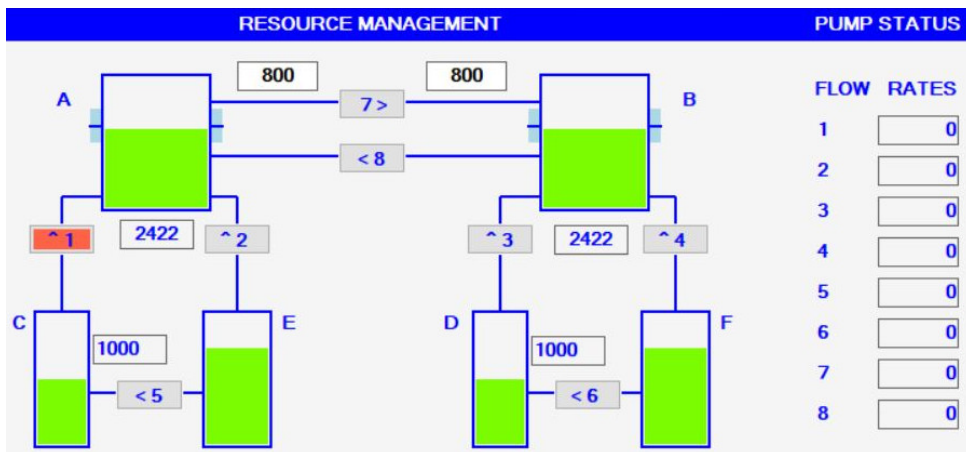


Figure 6.5 – NASA Multi-Attribute Task Battery II (MATB-II), RESMAN interface.

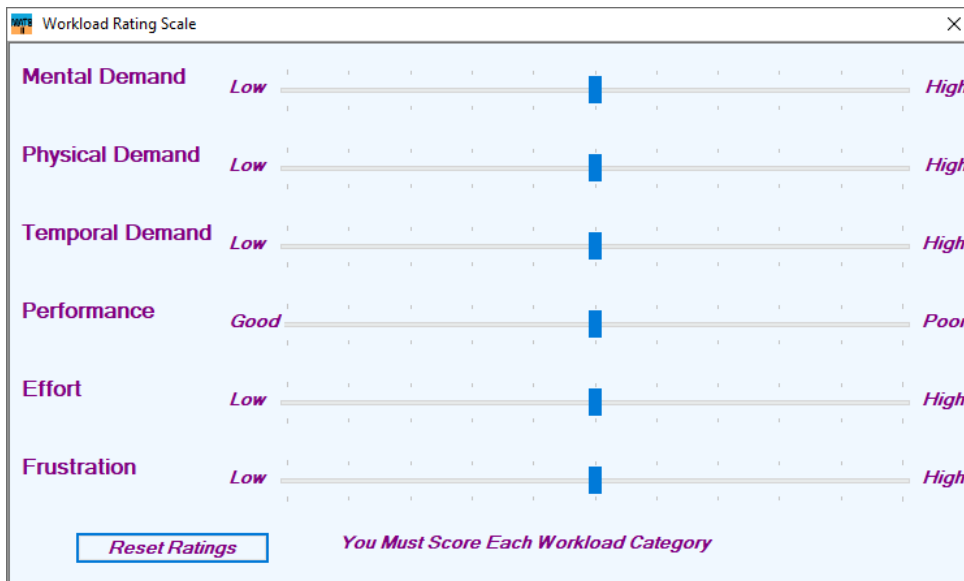


Figure 6.6 – NASA Multi-Attribute Task Battery II (MATB-II), WRS interface.

and showing its ends. This component also reminds the elapsed simulation time since the beginning of the session as it pauses during the WRS.

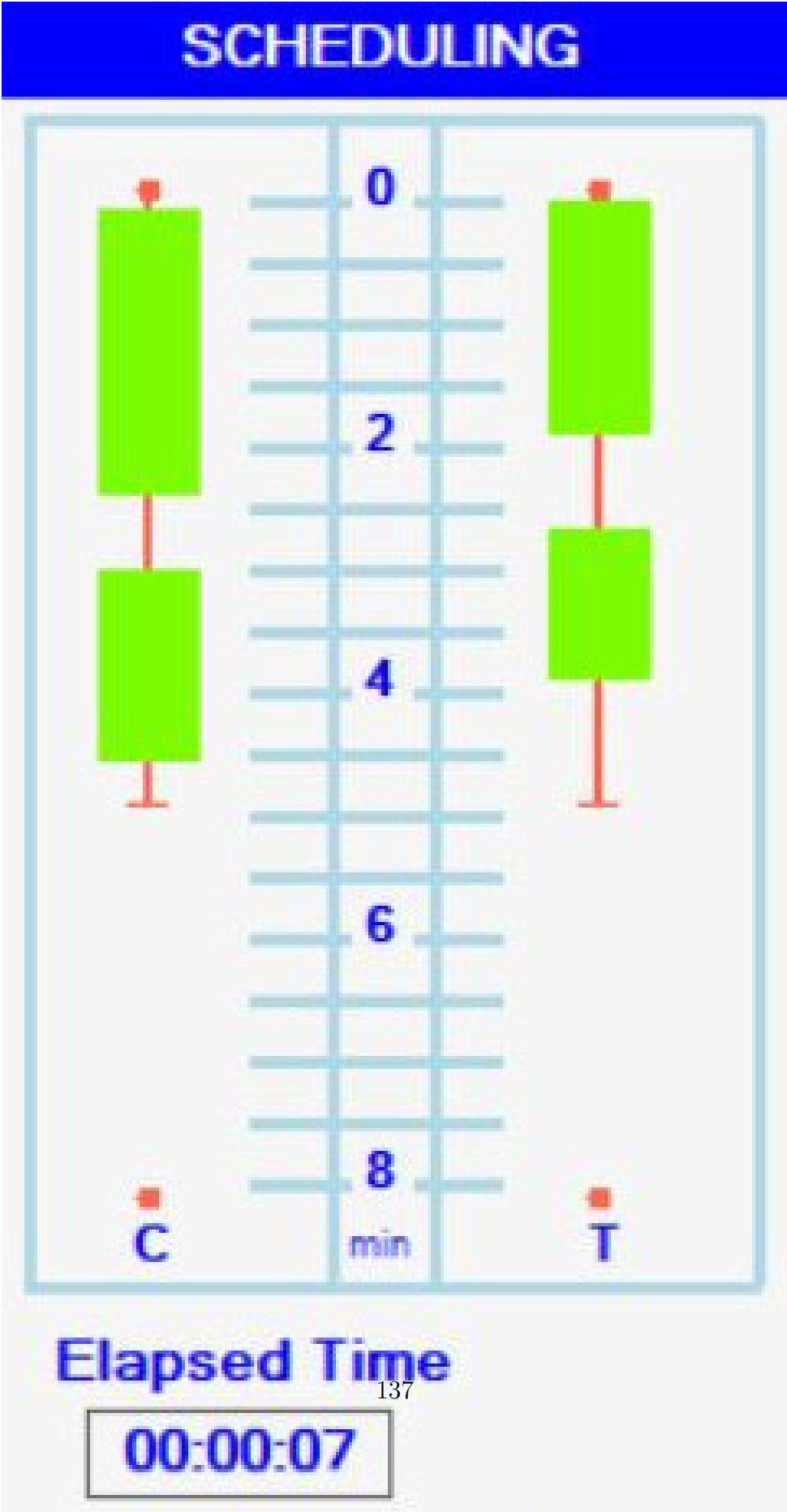


Figure 6.7 – NASA Multi-Attribute Task Battery II (MATB-II), SCHED interface.

MATB-II-CVE unexplored configurations

Some other configurations of the MATB-II-CVE workspace have been designed but never used. Based on a single system, providing multiple interfaces displaying the same task states was envisioned. These interfaces could be aligned side by side (Figure 6.8), with a angle between them (Figure 6.9 & 6.10) or back to back (Figure 6.11). Further design solutions were also discussed during early development, for example, providing multiple independent MATB-II systems, each bounded to either unique or multiple interfaces (Figure 6.12). Additional design considerations were envisioned in the early stages of development. One such proposal involved the implementation of multiple autonomous MATB-II systems, each associated with an interface (refer to Figure 6.12).

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cicppr@imt-atlantique.fr

5th December 2021

Object: IRB approval # 012021

Dear Prof. Duval, this letter will serve as confirmation that your research entitled « Percevoir une activité collaborative à distance avec la réalité mixte » has been approved by the IMT Atlantique's IRB (IRB00013722). You may now begin to implement this research as described in the application.

Please note that you may only conduct this research exactly in the form it was approved. You must seek specific board approval for any changes in this project. You must also seek re-approval if the project extends beyond the termination date noted below. In addition, if there are any unanticipated adverse reactions or events associated with the conduct of this research, you should immediately suspend the project and contact the chair of the IRB for consultation.

The Board wishes you success in the pursuit of your research goals.

Approval termination: 01/02/2022



Prof. Vincent Nourrit

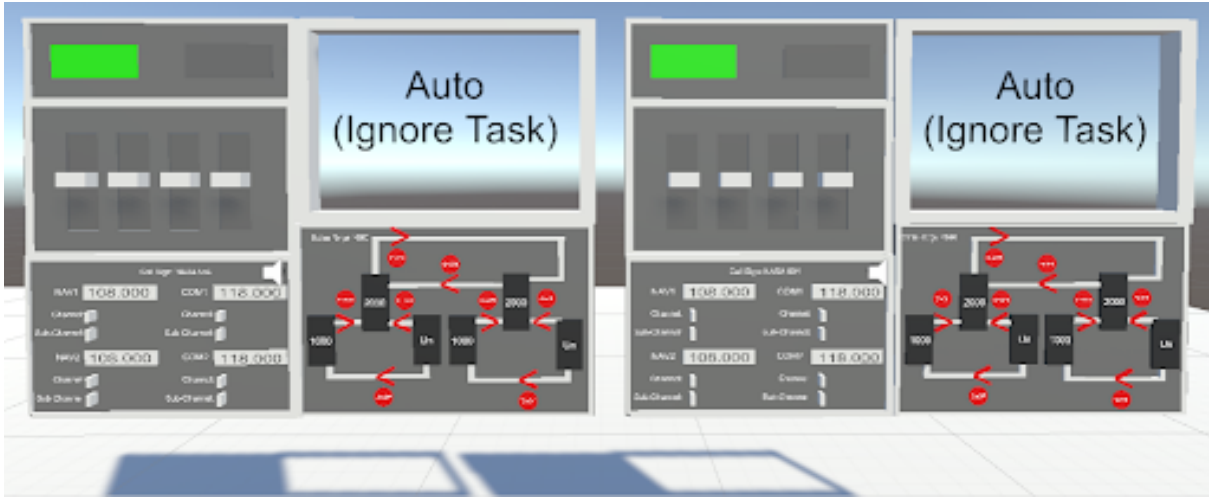


Figure 6.8 – Scene arrangement setting users facing two MATB-II interfaces side by side.

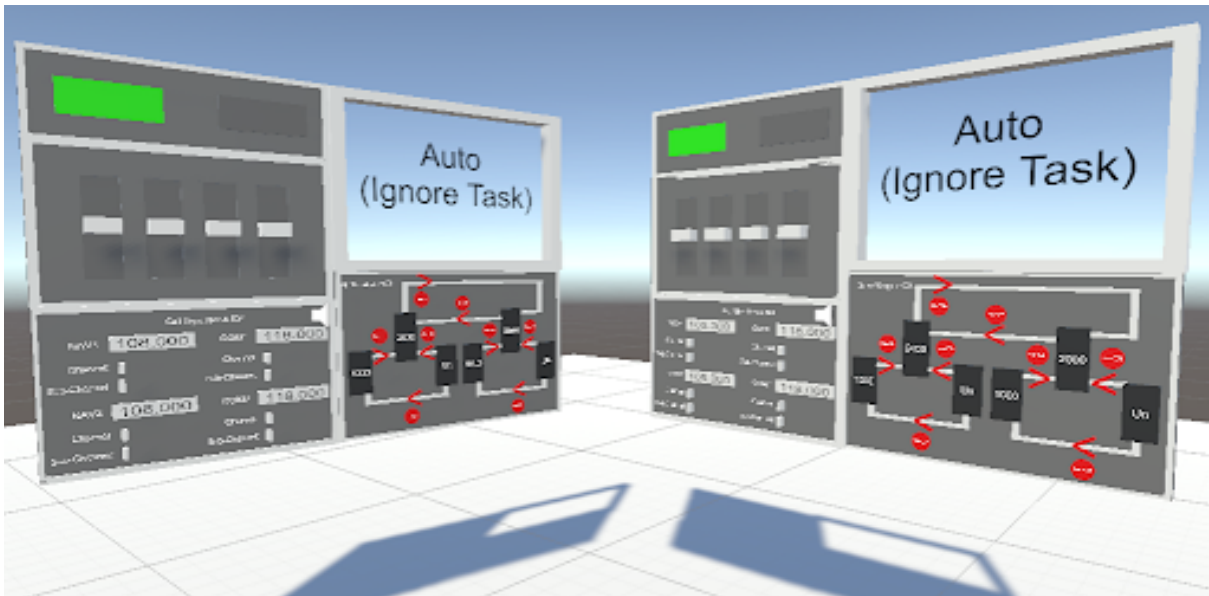


Figure 6.9 – Scene arrangement setting two MATB-II interfaces side by side with a small angle.

Project title: Perceiving distant collaborative activity with Mixed Reality

Research Project Goal:

We want to investigate how to improve collaborative awareness: awareness of each other within a collaborative virtual environment, focusing on sharing each other's progress. We are interested in scenarios where remote collaborators are both working on the NASA-MATB-II task set. The goal of this study is to better understand how sharing user status can improve collaborative awareness and task performance.

What will I be asked if I participate?

If you agree to participate in this study, you will be accompanied from the IMT Atlantique reception desk (Brest site) to the room where the experiment takes place (INFO or LUSI department). You will participate in an experiment during which you will complete the 4 tasks of the NASA-MATB-II system using an immersive headset and its controllers (HTC Vive Cosmos and Oculus Quest 2).

- **System Monitoring:** You'll have to respond to the absence of the green light, the presence of the red light, and monitor the four moving pointer dials for deviation from midpoint.
- **Communications:** This task presents pre-recorded auditory messages at selected intervals during the simulation. You'll have to determine which messages are addressed to you and respond by selecting the appropriate radio and frequency on the communications task panel.
- **Tracking:** You'll have to maintain the target at the center of the frame.
- **Resource Management:** The goal is to maintain the upper tanks around 2500 units each. This is done by turning On or Off any of the eight pumps. Pump failures can occur and are shown by a red light on the failed pump which repairs after some time.

We will record your speed and accuracy while you perform the tasks (about 30 minutes). During the experiment, several visual aids will be proposed to you, at the end, you will fill in a questionnaire to compare them (about 5 minutes).

Will my data be confidential?

We will collect the multiple choice and textual answers to the questionnaires and the event recordings ("logs") of the remote software that capture the evolution of the task (trajectories of the virtual objects, view positions and timestamps). The data obtained will be treated with the utmost confidentiality. Each participant will be assigned a unique identifier that will preserve his or her anonymity. The data captured automatically during the experiment will be linked to this unique identifier and cannot be directly linked to your identity. The only personal data (Name, First name, Age, Sex), will be kept in paper format in a secure place in order to guarantee your rights of retraction and rectification, only the scientific leader and the assistant researchers will have access to it. Age and gender information may be used for statistics on all participants. The identity of the participants will not be used or communicated under any circumstances. In accordance with the provisions of the French Data Protection Act, you may exercise your right to access, rectify or delete data concerning you by simply requesting the project's scientific manager.

Do I have to participate?

You are not obliged to participate in the study. If you decide to participate and change your mind later (either before starting the study or halfway through), you can withdraw without giving any reasons and, if you wish, your data will be destroyed.

Are there any risks to participating in this study?

Given the current situation (Covid-19), this experiment will strictly adhere to the health protocol defined within ITM Atlantic.

There is a risk that some susceptible participants may experience some of the symptoms of simulator sickness similar to those associated with motion sickness: discomfort, headache, stomach ache,

nausea, vomiting, paleness, sweating, fatigue, drowsiness, disorientation, apathy. These symptoms generally occur gradually, are easily detectable by the subject and are quickly resolved after the end of the immersive experience. The complete recovery of the most important symptoms is generally reached after a rest period of 15 to 20 minutes. The last phase of the experience will be extended as much as necessary in order to guarantee your safety whatever the post-experimental activity envisaged (walking, cycling, driving ...). The tests are in 3D and this could possibly cause visual fatigue, but their nature and duration have been designed to minimize this risk as much as possible.

What benefits do I get from participating?

There are no direct benefits associated with your participation other than contributing to the research and gaining knowledge on the subject of human-computer interaction.

Where can I get more information if I need it?

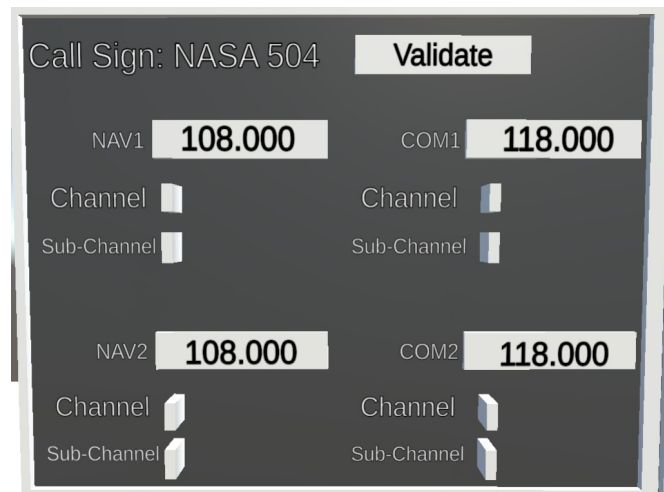
You can ask questions about the research at any time (before, during and after your participation) by contacting the scientific leader or the experimenter, respectively: Thierry Duval, research director, thierry.duval@imt-atlantique.fr or Thomas Rinnert, PhD student, thomas.rinnert@imt-atlantique.fr

Can I have access to the results of the study?

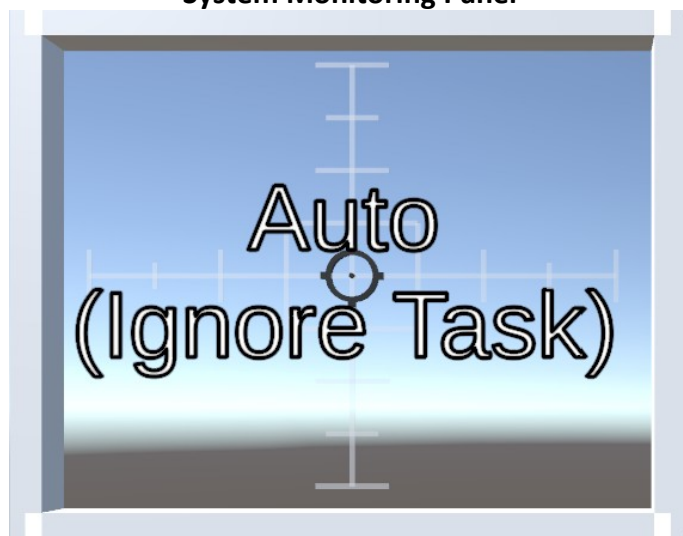
The results of this research may be presented in scientific conferences and published in conference proceedings or in a journal, you can have access to them by contacting the scientific manager.



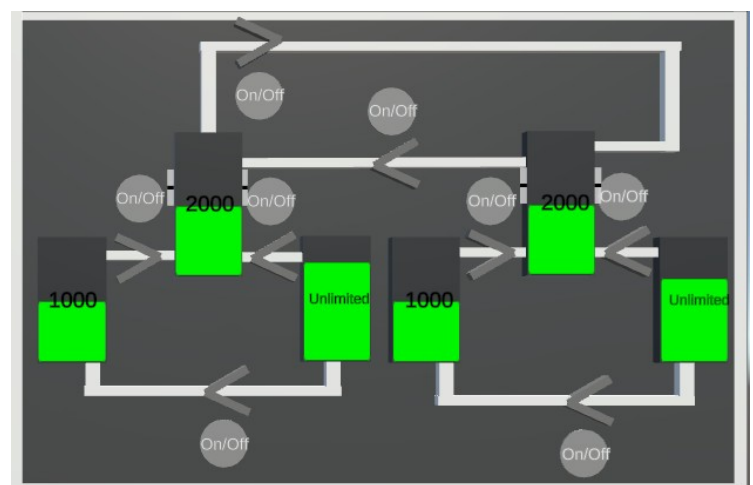
System Monitoring Panel



Communications Panel



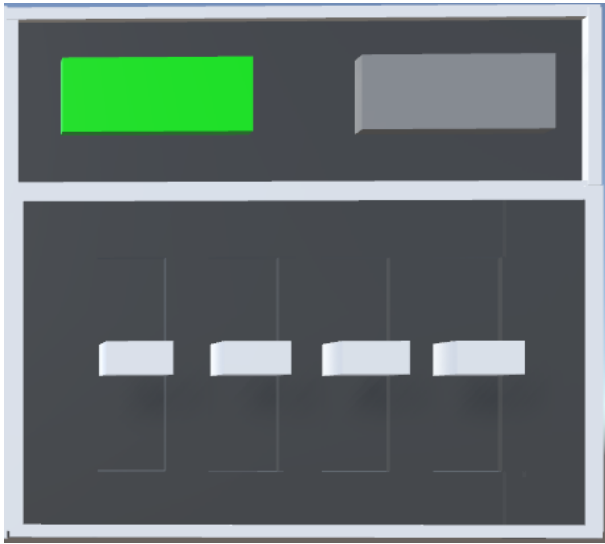
Tracking Panel



Resource Management Panel

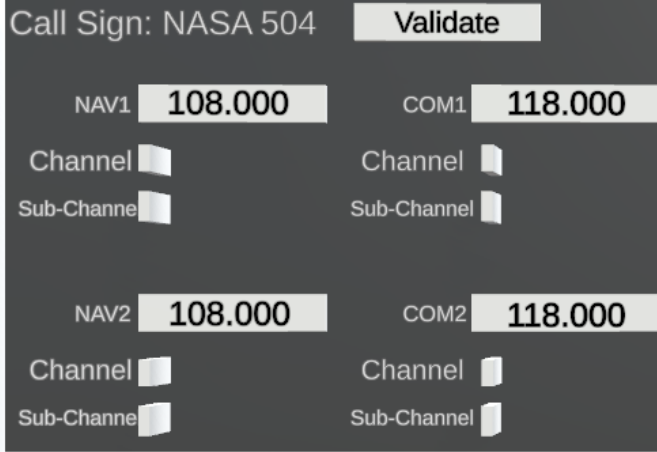
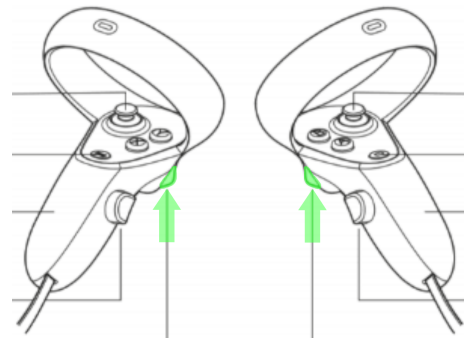
MATB-II-VR User guide

As a way to evaluate research propositions, the MATB has been adapted to a collaborative virtual workspace where multiple participants would execute tasks on the battery. Virtual panels may be placed in the workspace to help participants to work efficiently by displaying information referring to each participant status. The four tasks can be performed by any participant but we advise to assign the responsibility of each task among participants: the System Monitoring (SYSMON), Communication (COMM), Tracking (TRACK) and Resource Management (RESMAN) tasks.



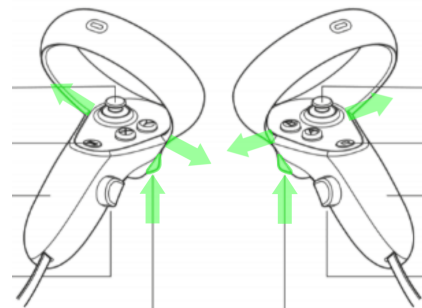
System Monitoring (SYSMON)

You have to respond to the absence of the green light or the presence of the red light by **clicking** on them. You also need to monitor the four moving pointer dials, if you observe deviation from midpoint, **click** on the dial to recenter it.



Communications (COMM)

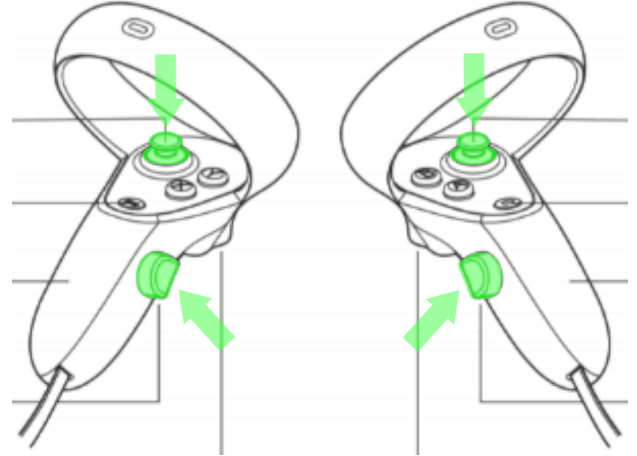
This task presents auditory messages, you have to determine which messages are addressed to you and respond by selecting the appropriate radio and frequency on the communications task panel. You can modify radio frequencies by **clicking** and **dragging** the slider of the entire part and that of the decimal part.





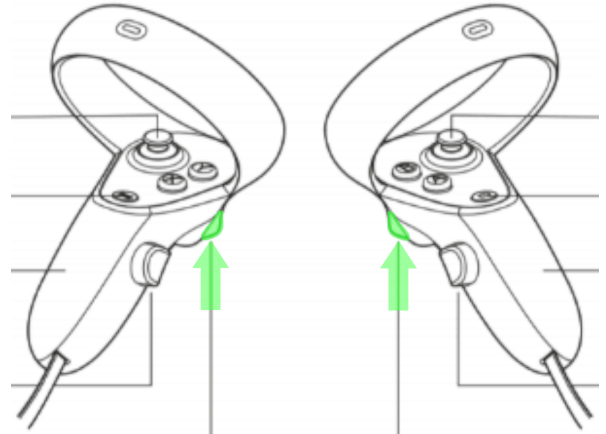
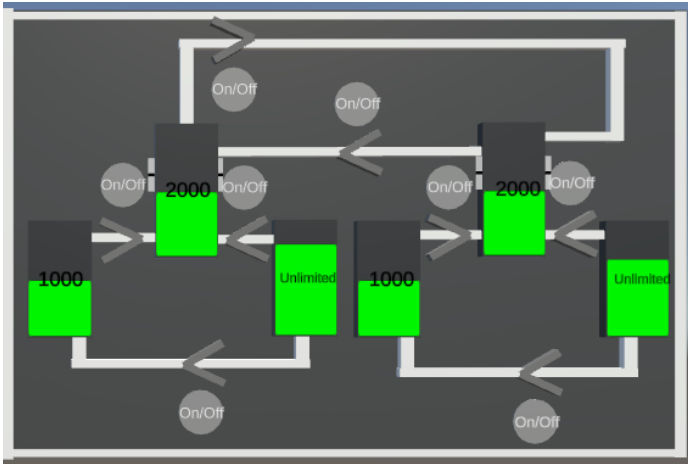
Tracking (TRACK)

When the task is active, you have to maintain the target at the center of the frame. To control the target, use the **joystick** of a controller while pressing the **grip button** on that same controller.



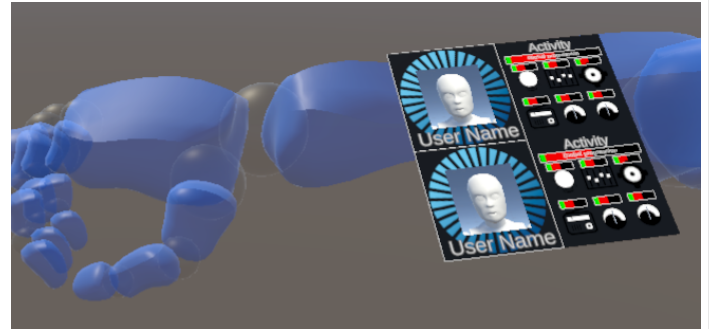
Resource Management (RESMAN)

The goal is to maintain the upper tanks around 2500 units as the fuel is consumed from them. You can fill the tanks with pumps represented by arrows on the diagram. By **clicking** on the On/Off buttons next to the arrows, you can toggle the operation of the pumps. Pump failures can occur and are shown by a red light on the failed pump which repairs after time.



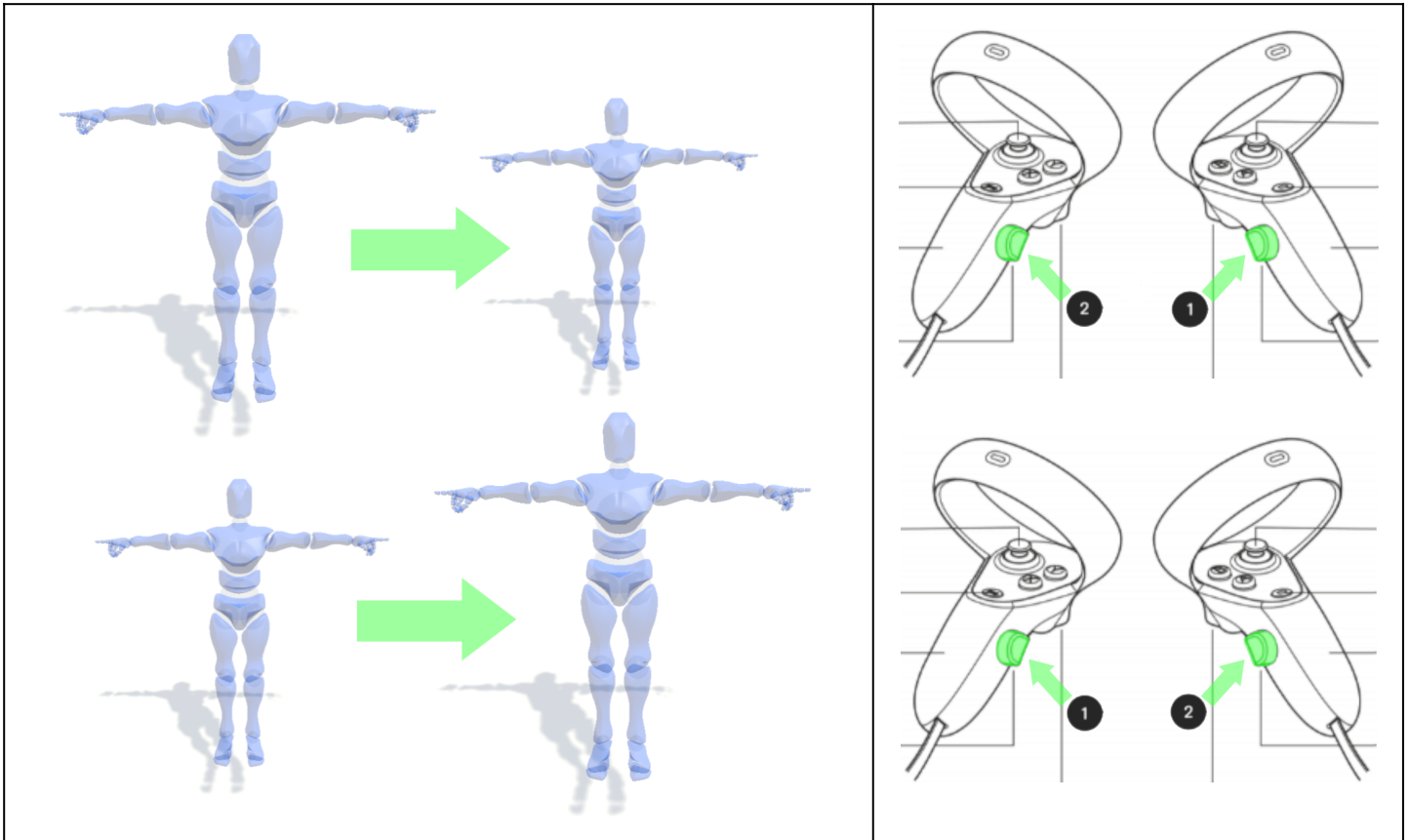


Activity progress of your team is displayed on this panel with bars and icons. The bars show the progress on tasks from the start of the scenario, the red bar corresponding to the time passing and the green to your actions. Icons provide instantaneous information turning more and more red as a task approaches a failure. All indicators refer to a task, beginning with the top-left lightbulb showing SYSMON lights task score and status. The scales next to it also refer to the SYSMON task, each scale is binded to a dial. The target refers to the TRACKING task, the radio to the COMM task and the two gauges to the RESMAN task.



Avatar customisation

Your avatar in the virtual environment may not have the same silhouette as you. You can resize it by holding your arms out in front of you before pressing the buttons.



Project no

CONSENT FORM (adults)

Project title:

Perceiving distant collaborative activity with Mixed Reality

Delete as appropriate and initial.

1. Did you read the participant information sheet?	YES/NO Initials
2. Did you get enough information on the study and what your participation implies ?	YES/NO Initials
3. Do you understand that you do not need to participate in the study and that if you do, you are free to withdraw: * at any time during the study; * without having to explain yourself; * and without prejudice to you?	YES/NO Initials
4. Do you agree to participate in this study?	YES/NO Initials.

Name/Surname : **Age :**

Signature : **Date :**

Experimenter : **Signature :** **Date:**

This project has been approved by the Comité Institutionnel Consultatif pour la Protection des Personnes dans la Recherche d'IMT Atlantique

XP1 - End of experiment questionnaire

Please complete this sheet to enable us to analyze the results of this experiment.

Participant's ID

Gender

Age

How much are you used to the following:

	Not at all	Casual use	Used to it	Comfortable	Expert
Video games	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
3D environments	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Immersive technologies	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Did the progress bars help you?

Not at all	Sometimes	Absolutely
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

How would you rate the progress bars?

0	1	2	3	4
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Did the icons help you?

Not at all	Sometimes	Absolutely
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

How would you rate the icons?

0	1	2	3	4
<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Did you always know when your partner needed help ?

With indicators Yes No

Without indicators Yes No

Could you always help your partner ?

With indicators Yes No

Without indicators Yes No

Any remarks ?

Chapter 4

Here, the first appendix is the ethics committee approval for the study presented in Chapter 4. It is followed by the participant information sheet, consent form and questionnaires used for this study.

Human Ethics: Application approved

no_reply@unisa.edu.au <no_reply@unisa.edu.au>

Tue 20/09/2022 12:45

To: Rinnert, Thomas Jean-Noel, Hubert, Rene-Marc - rinty003 <thomas.rinnert@mymail.unisa.edu.au>; Bruce Thomas <Bruce.Thomas@unisa.edu.au>; James Walsh <James.Walsh@unisa.edu.au>; Human Ethics <humanethics@unisa.edu.au>

Dear Applicant

Re: Ethics protocol "Comparative study of user status representation within a collaborative virtual environment" (Application ID: 204935)

Thank you for submitting your ethics protocol for consideration. Your protocol has been considered by the E1 Committee Review Group.

I am pleased to advise that your protocol has been granted ethics approval and meets the requirements of the National Statement on Ethical Conduct in Human Research. Please note that the E1 Committee Review Group's decision will be reported to the next meeting of the Human Research Ethics Committee for endorsement.

Please regard this email as formal notification of approval.

Ethics approval is always made on the basis of a number of conditions detailed at <https://i.unisa.edu.au/staff/research/research-ethics/human-research-ethics/ethics-management-for-research-projects/> (under the heading 'What are the Standard Conditions of Approval?'). It is important that you are familiar with, and abide by, these conditions. It is also essential that you conduct all research according to UniSA guidelines, which can be found at <https://i.unisa.edu.au/staff/research/research-ethics/human-research-ethics/ethics-policies-guidelines/>

Please note, if your project is a clinical trial you are required to register it in a publicly accessible trials registry prior to enrolment of the first participant (e.g. Australian New Zealand Clinical Trials Registry <http://www.anzctr.org.au/>) as a condition of ethics approval.

Best wishes for your research.

Executive Officer
UniSA's Human Research Ethics Committee
CRICOS provider number 00121B

This is an automated email and cannot be replied to. Please direct your query to humanethics@unisa.edu.au.



University of
South Australia
STEM Academic Unit

Participant Information Sheet

Title	Comparative study of user status representation within a collaborative virtual environment
Project Number	204935
Chief Investigator/ Principal Investigator	Thomas Rinnert
Supervisor	Bruce Thomas & James Walsh

Introduction – What does my participation involve?

This Participant Information Sheet tells you about the research project. It explains the processes involved with taking part. Knowing what is involved will help you decide if you want to take part in the research. Please read this information carefully. Ask questions about anything that you don't understand or want to know more about.

Participation in this research is voluntary. If you don't wish to take part, you don't have to. If you decide you want to take part in the research project, you will be asked to sign the consent section. By signing it you are telling us that you:

- Understand what you have read
- Consent to take part in the research project
- Consent to the use of your information as described.

You will be given a copy of this Participant Information Sheet to keep.

What is the purpose of this research?

We want to investigate how to improve collaborative awareness: awareness of each other within a collaborative virtual environment, focusing on sharing each other's progress. We are interested in scenarios where a supervisor has to manage the workload of a team. The goal of this study is to better understand how sharing user status can improve collaborative awareness and task performance.

What does participation in this research involve?

If you agree to participate in this study, you will be escorted from the lobby of Building W on UniSA's Mawson Lakes campus to the room where the experiment takes place (W1-15). You will participate in an experiment during which you will be asked to distribute tasks to virtual operators using an immersive headset and its controllers (HTC Vive Cosmos).

The virtual operators will face a NASA-MATB-II interface, a system composed of four tasks: system monitoring (SYSMON), communication (COMM), tracking (TRACK) and resource management (RESMAN). You will receive tasks to assign to operators, these tasks will be represented by cubes on which the name of the associated task will be written. The operators will each have a task queue to execute, each task will increase their stress level. The higher the stress level of an operator, the more likely he is to fail at his task. Finally, not all operators perform their tasks at the same speed.

We will record your choices of task assignment to operators, the number of tasks successfully completed by each operator and the time required for the team to complete all tasks (approximately 40 minutes). During the experiment, several visual aids will be proposed to you, at the end, you will fill a questionnaire to compare them (about 10 minutes).

What are the possible benefits of taking part?

A 20\$ Coles Myer gift card, contribution to the research and gain of knowledge on the subject of human-computer interaction.

What are the possible risks and disadvantages of taking part?

Given the current situation (Covid-19), this experiment will strictly adhere to the health protocol defined within UniSA.

There is a risk that some susceptible participants may experience some of the symptoms of simulator sickness similar to those associated with motion sickness: discomfort, headache, stomach ache, nausea, vomiting, paleness, sweating, fatigue, drowsiness, disorientation, apathy. These symptoms generally occur gradually, are easily detectable by the subject and are quickly resolved after the end of the immersive experience. The complete recovery of the most important symptoms is generally reached after a rest period of 15 to 20 minutes. The last phase of the experience will be extended as much as necessary in order to guarantee your safety whatever the post-experimental activity envisaged (walking, cycling, driving ...). The tests are in 3D and this could possibly cause visual fatigue, but their nature and duration have been designed to minimise this risk as much as possible.

Do I have to take part in this research project?

Participation in any research project is voluntary. If you do not wish to take part, you do not have to. If you decide to take part and later change your mind, you are free to withdraw from the project at any stage and, if you wish, your data will be destroyed.

What will happen to information about me?

We will collect the multiple choice and textual answers to the questionnaires and the software logs that capture the evolution of the task (trajectories of the virtual objects, view positions and timestamps). At the end of the experiment, you will be asked to verbally clarify your answers to the questionnaires to the experimenter, this interview will be recorded. The data obtained will be treated with the utmost confidentiality. Each participant will be assigned a unique identifier that will preserve his or her anonymity. The data captured automatically during the experiment will be linked to this unique identifier and cannot be directly linked to your identity. The only personal data (Name, First name, Age, Sex), will be kept in paper format in a secure place in order to guarantee your rights of retraction and rectification, only the scientific leader and the assistant researchers will have access to it. Age and gender information may be used for statistics on all participants. The identity of the participants will not be used or communicated under any circumstances. In accordance with the provisions of the French Data Protection Act, you may exercise your right to access, rectify or delete data concerning you by simply requesting the project's scientific manager. All records containing personal information will remain confidential and no information which could lead to identification of any individual will be released unless required by law, however the researcher cannot guarantee the confidentiality or anonymity of material transferred by email or the internet

What if something goes wrong?

When the participant has reported one of the symptoms of Cybersickness, special care will be taken to ensure their full recovery (provision of a comfortable couch, monitoring and assistance from the experimenter) as much time as necessary to ensure their safety whatever the postexperimental activity planned by him (walking, cycling, driving ...).

What happens when the research project ends?

The results of this research may be presented in scientific conferences and published in conference proceedings or in a journal, you can have access to them by contacting the scientific manager.

Who is organising and funding the research?

This research project is being conducted by Thomas Rinnert, PhD student (funded by CNRS). No member of the research team will receive a personal financial benefit from your involvement in this research project (other than their ordinary wages).

Who has reviewed the research project?

The ethical aspects of this research project have been approved by the Human Research Ethics Committee (HREC) of the University of South Australia as required by the Australian government research requirements, specified in the National Statement on Ethical Conduct in Human Research (2007 - updated 2018). This statement has been developed to protect the interests of people who agree to participate in human research studies.

Further information and who to contact

The person you may need to contact will depend on the nature of your query. If you want any further information concerning this project or if you have any problems which may be related to your involvement in the project, you can contact the researcher:

Research contact person

Name	Thomas Rinnert
Position	PhD student
Telephone	0410 638 954
Email	thomas.rinnert@mymail.unisa.edu.au

If you have any complaints about any aspect of the project, the way it is being conducted or any questions about being a research participant in general, please contact:

Reviewing HREC name	University of South Australia Human Research Ethics Committee
HREC Executive Officer	Human Ethics Officer
Telephone	+618 8302 6330
Email	humanethics@unisa.edu.au

Reviewing HREC approving this research and HREC Executive Officer details



This project has been approved by the University of South Australia's Human Research Ethics Committee. If you have any ethical concerns about the project, or questions about your rights as a participant, please contact the Executive Officer of this Committee, Tel: +61 8 8302 6330; Email: humanethics@unisa.edu.au

SECTION 1: CONTACT AND PROJECT DETAILS

Researcher's Full Name	Thomas Rinnert
Contact Details	thomas.rinnert@mymail.unisa.edu.au
Supervisor's Name <i>(students only)</i>	Prof Bruce Thomas, Dr James Walsh
Contact Details	{bruce.thomas, james.walsh}@unisa.edu.au
Project Number	204935
Project Title	Comparative study of user status representation within a collaborative virtual environment

SECTION 2: PARTICIPANT CERTIFICATION

In signing this form, I confirm that:

- I have read the Participant Information Sheet, and the nature and the purpose of the research project has been explained to me. I understand and agree to take part.
- I understand the nature of my involvement in the project.
- I understand that I may not directly benefit from taking part in the project.
- I understand that I can withdraw from the project at any stage and that this will not affect my status now or in the future.
- I am over 18 years of age.
- I understand that while information gained during the project may be published, I will not be identified and my personal results will remain confidential, unless required by law.
- I understand that I will be audio and videotaped during the project.
- I understand that the tapes will be stored securely on digital file in the School's data repository for five years upon completion of the project. Only researchers and system administrators will have access to it, and that this data will not be disclosed unless required by law.
- I understand that non-identifiable data collected from this project may be used for another purpose by the researcher and/or shared openly with other researchers for future research projects (for which ethics approval will be sought).

<i>Participant's Signature</i>	<i>Printed Name</i>	<i>Date</i>
--------------------------------	---------------------	-------------

SECTION 3: RESEARCHER CERTIFICATION

I have explained the study to the participant and consider that he/she understand what is involved.

<i>Researcher Signature</i>	<i>Printed Name</i>	<i>Date</i>
-----------------------------	---------------------	-------------

Demographic questionnaire

* Indicates required question

1. Participant ID *

2. Gender *

Mark only one oval.

Male

Female

Other:

3. Age *

4. You are *

Mark only one oval.

Left-handed

Ambidextrous

Right-handed

5. Are you used to video games? *

Mark only one oval.

1 2 3 4 5

Not A lot

6. Are you used to 3D environments? *

Mark only one oval.

1 2 3 4 5

Not A lot

7. Are you used to Immersive technologies? *

Mark only one oval.

1 2 3 4 5

Not A lot

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Google Forms

Condition assessment

First page to be filled by the experimenter

* Indicates required question

1. Participant ID *

2. Trial number *

Mark only one oval.

1	2	3	4	5
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

3. Condition *

Mark only one oval.

- No Cue *Skip to question 4*
- Literal - No Stress *Skip to question 5*
- Literal - Stress *Skip to question 15*
- Symbolic - No Stress *Skip to question 26*
- Symbolic - Stress *Skip to question 36*

No Cue

4. Did you manage to identify the slow and fast operators ? *

There were 2 fast operators, 2 medium speed operators and 2 slow operators.

Mark only one oval.

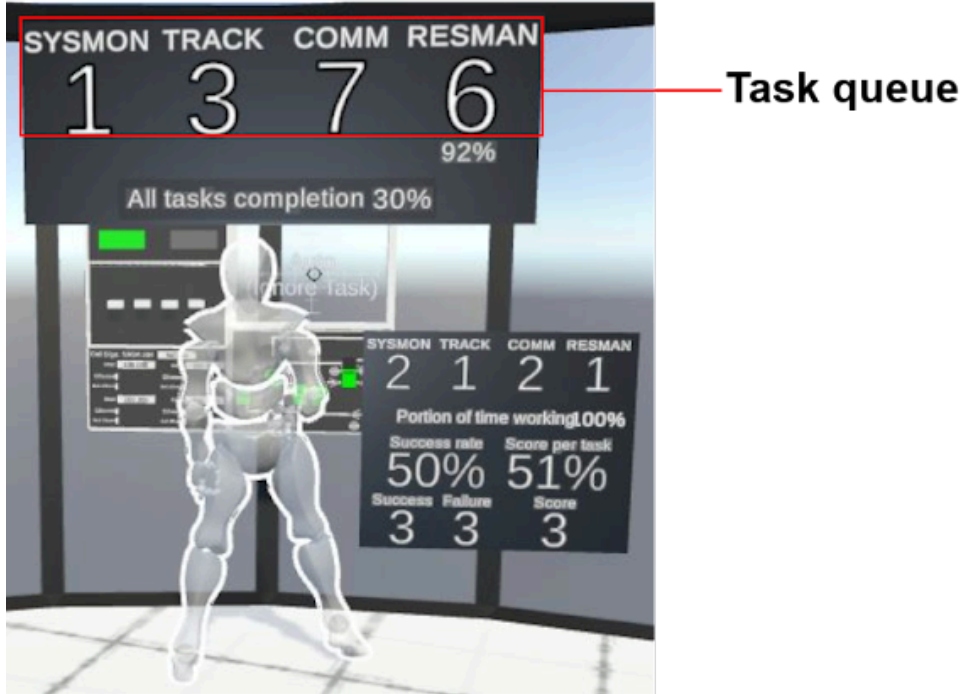
1	2	3	4	5	
Not <input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	Clearly identified all of them

Skip to question 47

Components assessment (Literal - No Stress)

You have been asked to get all tasks done as quickly as possible while maximizing the success rate of the tasks.

5. Did the task queue feedback help? *

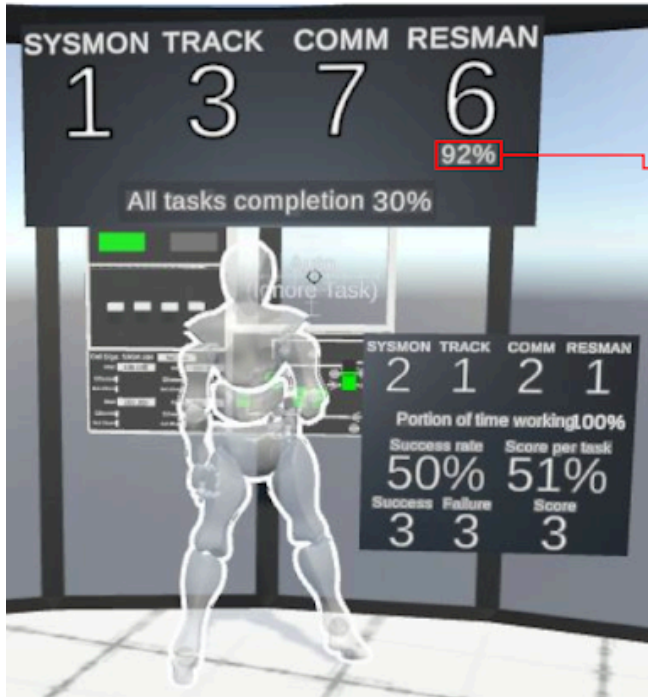


Mark only one oval.

1 2 3 4 5

Not A lot

6. Did the completion of current task feedback help? *



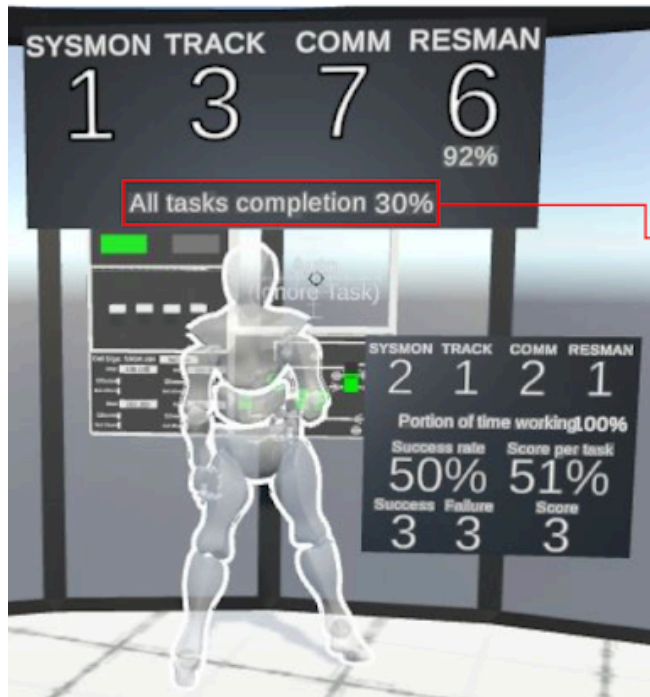
Current task completion

Mark only one oval.

1 2 3 4 5

Not A lot

7. Did the completion of all tasks feedback help? *



All tasks completion

Mark only one oval.

1 2 3 4 5

Not A lot

8. Did the task history help? *



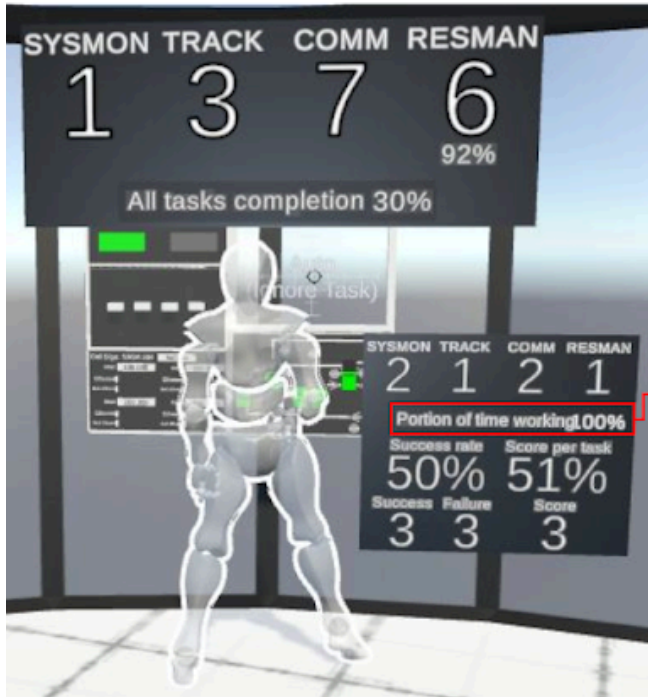
Task history

Mark only one oval.

1 2 3 4 5

Not A lot

9. Did the feedback on the portion of time passed working help? *



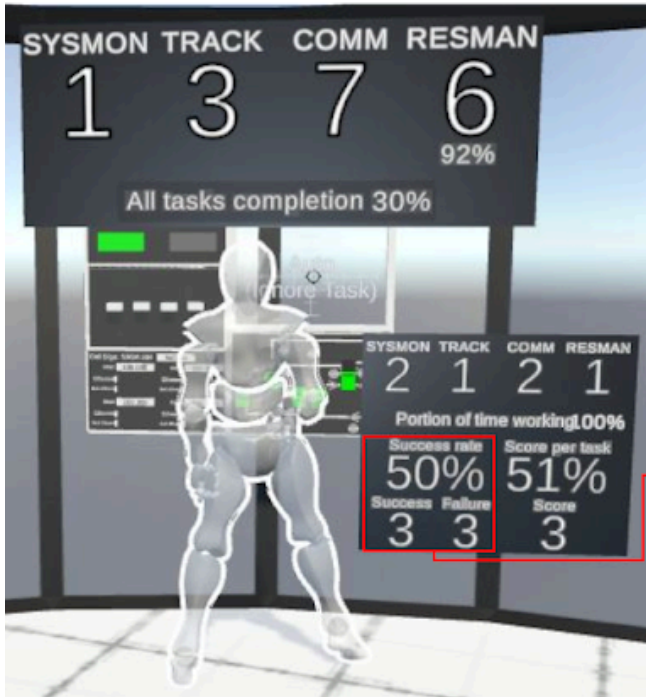
Portion of time working

Mark only one oval.

1 2 3 4 5

Not A lot

10. Did the Success/Failure feedback help? *



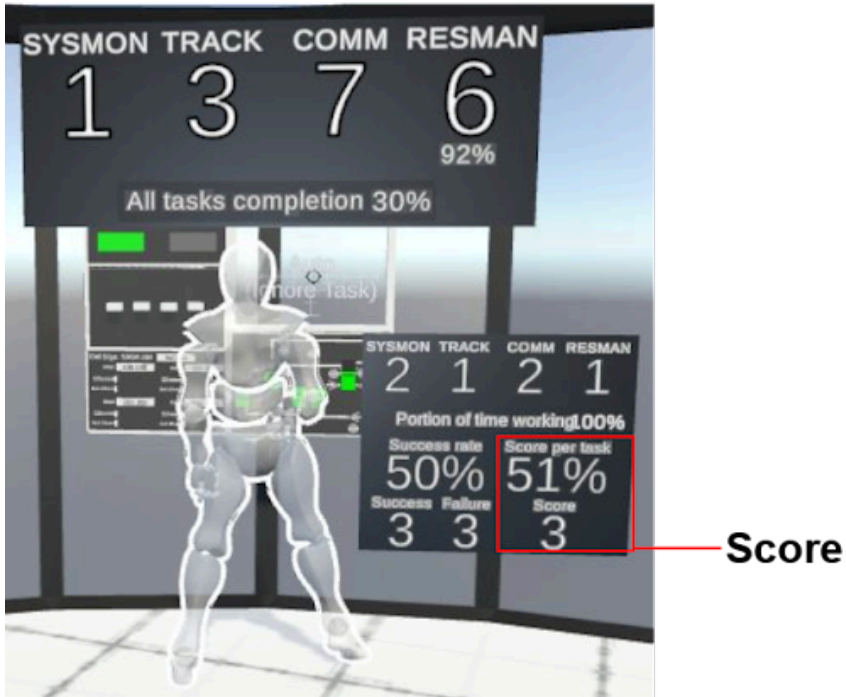
Success

Mark only one oval.

1 2 3 4 5

Not A lot

11. Did the Score feedback help? *



Mark only one oval.

1 2 3 4 5

Not A lot

13. What strategy did you use to dispatch tasks? *

14. Did you manage to identify the slow and fast operators ? *

There were 2 fast operators, 2 medium speed operators and 2 slow operators.

Mark only one oval.

1 2 3 4 5

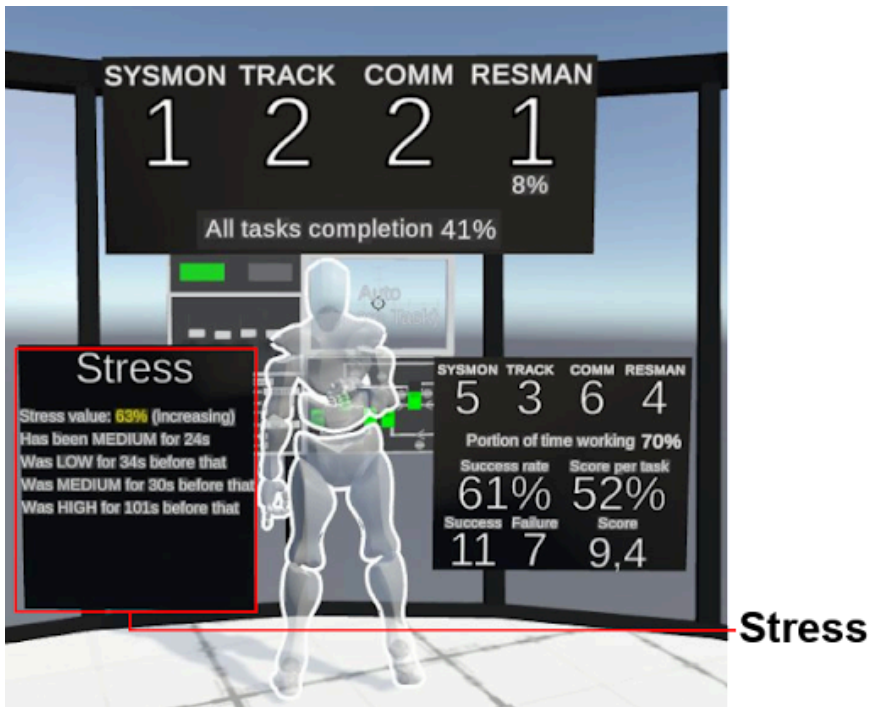
Not Clearly identified all of them

Skip to question 47

Component assessment (Literal - Stress)

You have been asked to get all tasks done as quickly as possible while maximizing the success rate of the tasks.

15. Did the stress feedback help? *

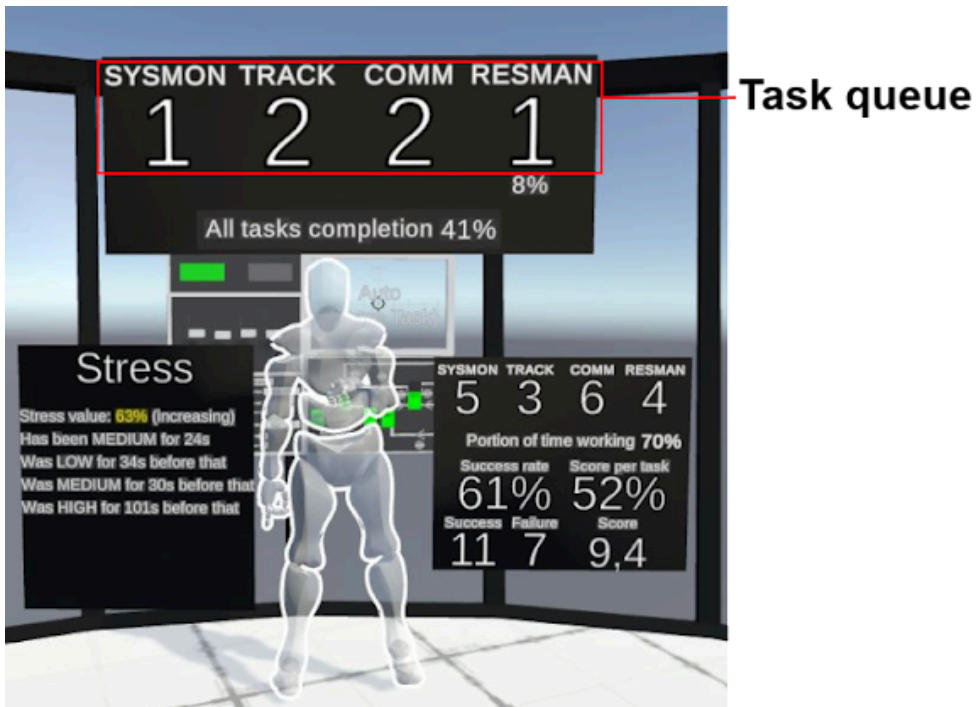


Mark only one oval.

1 2 3 4 5

Not A lot

16. Did the task queue feedback help? *

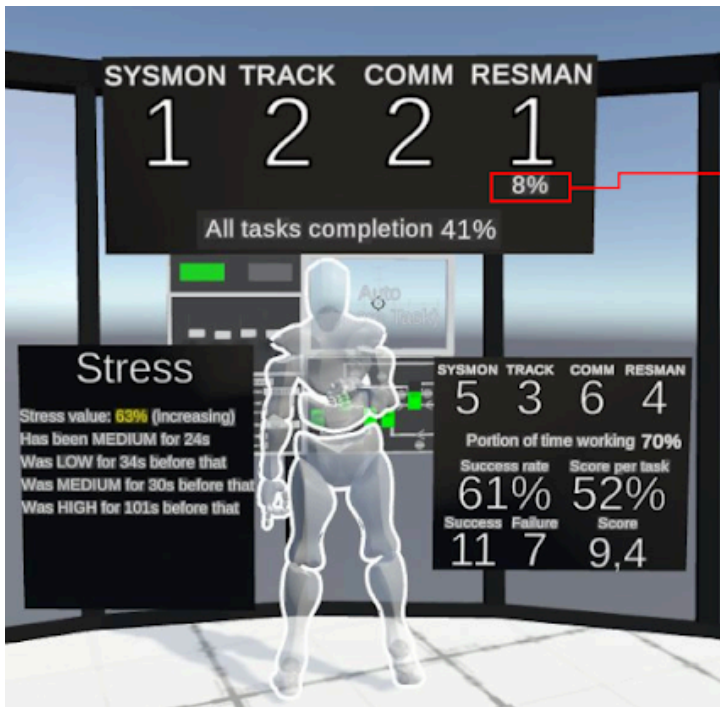


Mark only one oval.

1 2 3 4 5

Not A lot

17. Did the completion of current task feedback help? *



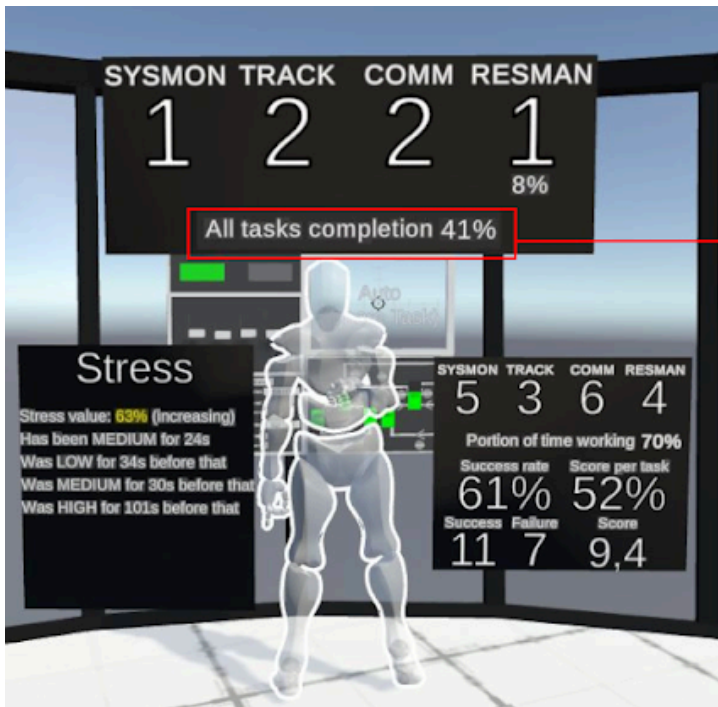
Current task completion

Mark only one oval.

1 2 3 4 5

Not A lot

18. Did the completion of all tasks feedback help? *



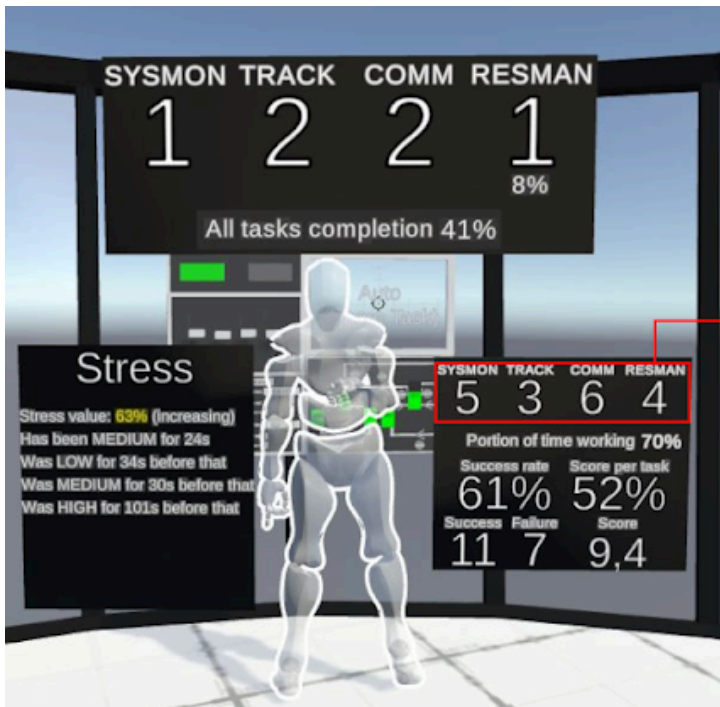
All tasks completion

Mark only one oval.

1 2 3 4 5

Not A lot

19. Did the task history help? *



Task history

Mark only one oval.

1 2 3 4 5

Not A lot

20. Did the feedback on the portion of time passed working help? *



Portion of time working

Mark only one oval.

1 2 3 4 5

Not A lot

21. Did the Success/Failure feedback help? *



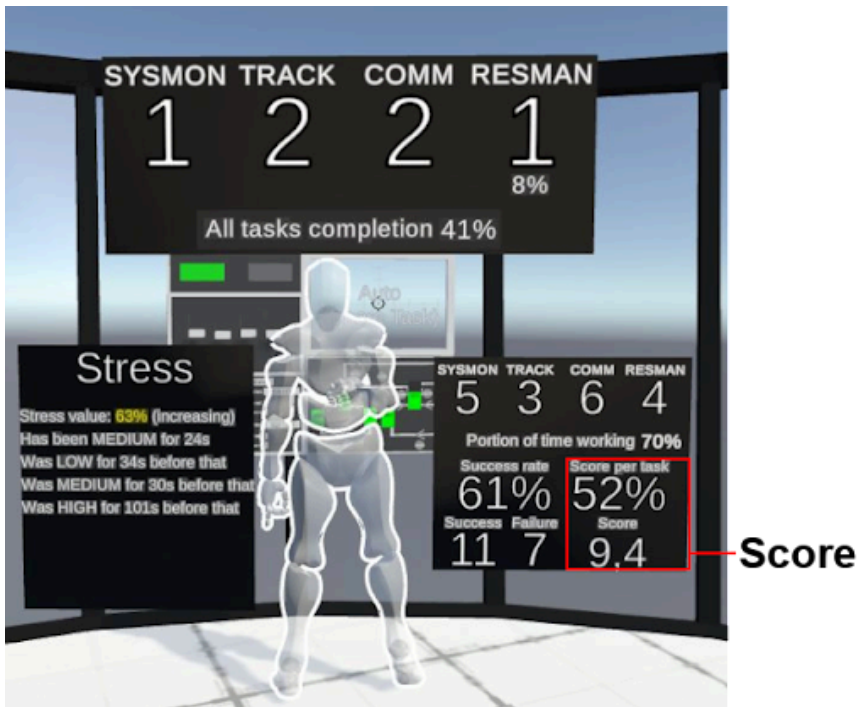
Success

Mark only one oval.

1 2 3 4 5

Not A lot

22. Did the Score feedback help? *



Mark only one oval.

1 2 3 4 5

Not A lot

24. What strategy did you use to dispatch tasks? *

25. Did you manage to identify the slow and fast operators ? *

There were 2 fast operators, 2 medium speed operators and 2 slow operators.

Mark only one oval.

1 2 3 4 5

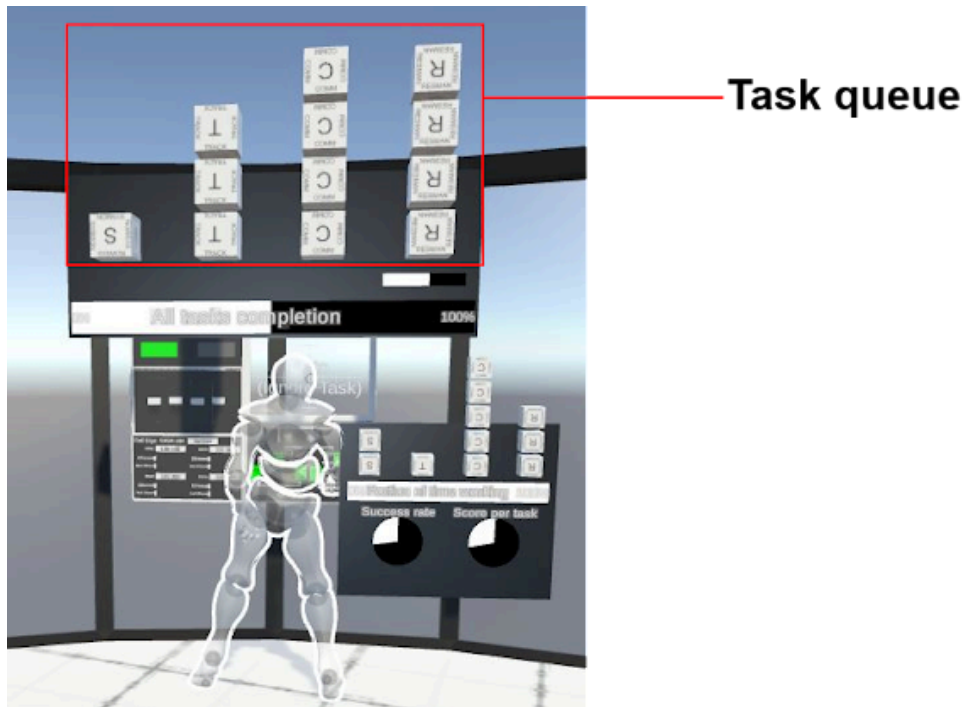
Not Clearly identified all of them

Skip to question 47

Component assessment (Symbolic - No Stress)

You have been asked to get all tasks done as quickly as possible while maximizing the success rate of the tasks.

26. Did the task queue feedback help? *

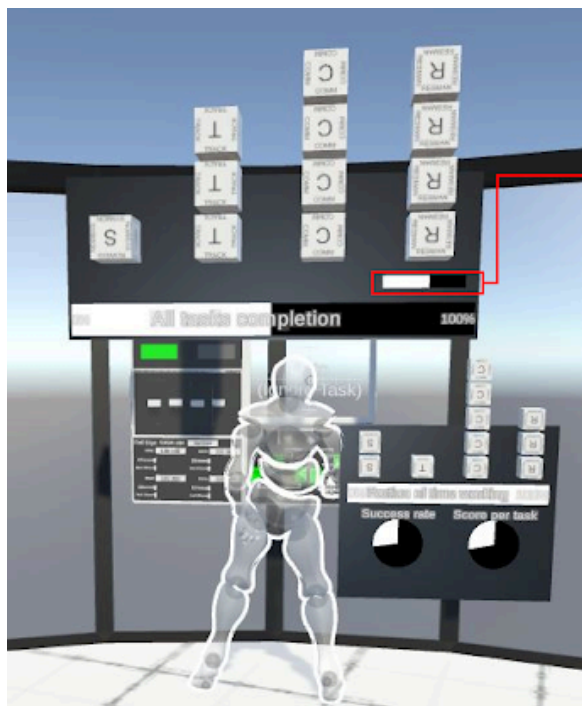


Mark only one oval.

1 2 3 4 5

Not A lot

27. Did the completion of current task feedback help? *



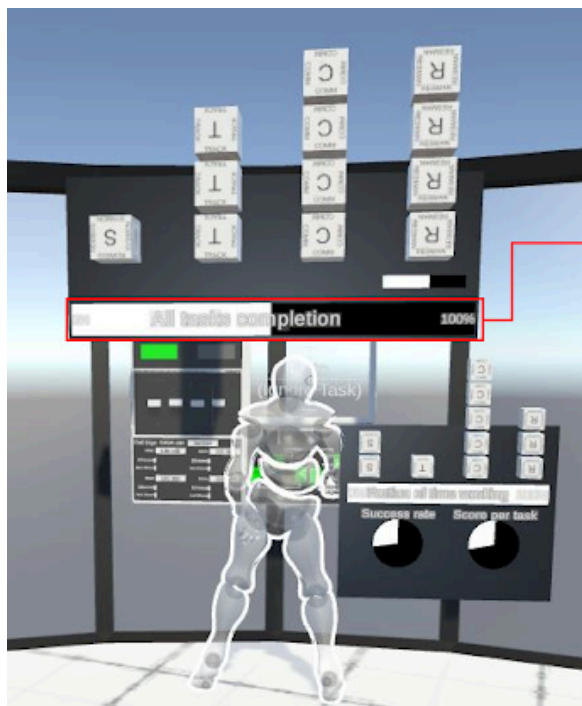
Current task completion

Mark only one oval.

1 2 3 4 5

Not A lot

28. Did the completion of all tasks feedback help? *



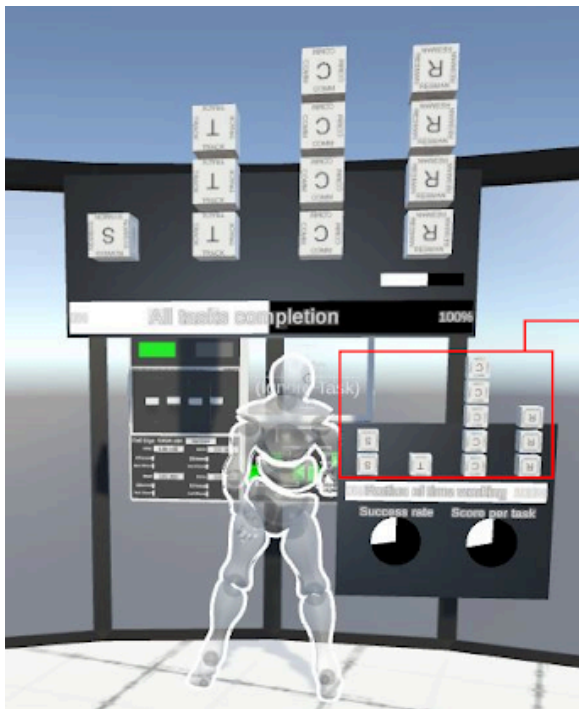
All tasks completion

Mark only one oval.

1 2 3 4 5

Not A lot

29. Did the task history help? *



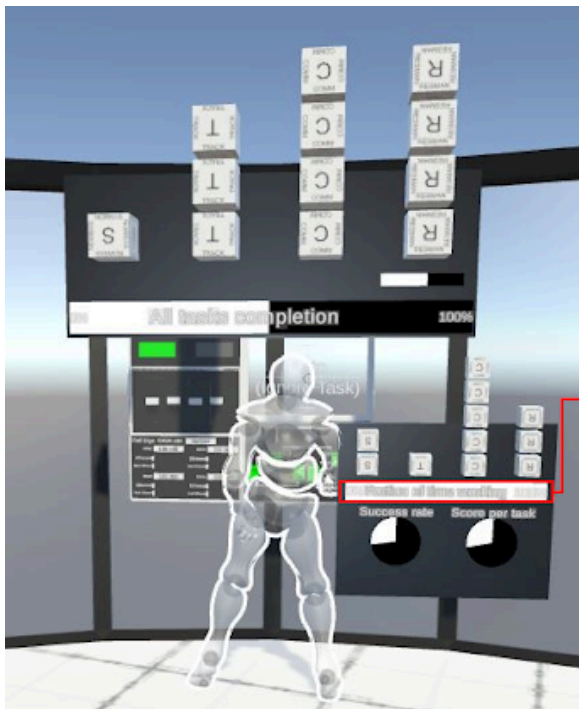
Task history

Mark only one oval.

1 2 3 4 5

Not A lot

30. Did the feedback on the portion of time passed working help? *



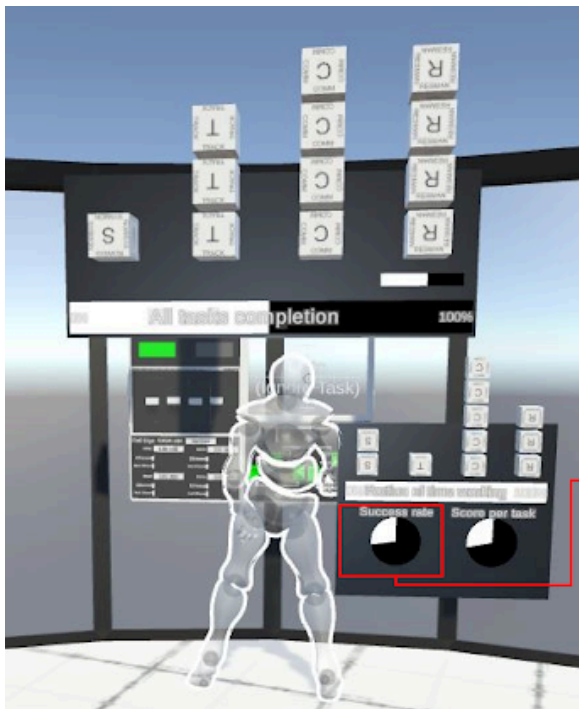
Portion of time working

Mark only one oval.

1 2 3 4 5

Not A lot

31. Did the Success/Failure feedback help? *



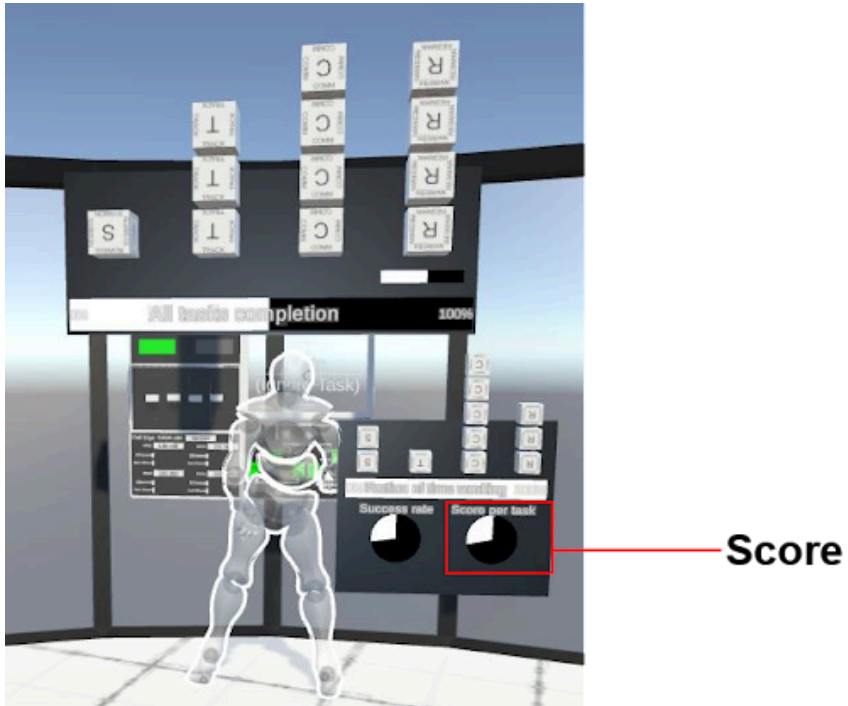
Success

Mark only one oval.

1 2 3 4 5

Not A lot

32. Did the Score feedback help? *



Mark only one oval.

1 2 3 4 5

Not A lot

34. What strategy did you use to dispatch tasks? *

35. Did you manage to identify the slow and fast operators ? *

There were 2 fast operators, 2 medium speed operators and 2 slow operators.

Mark only one oval.

1 2 3 4 5

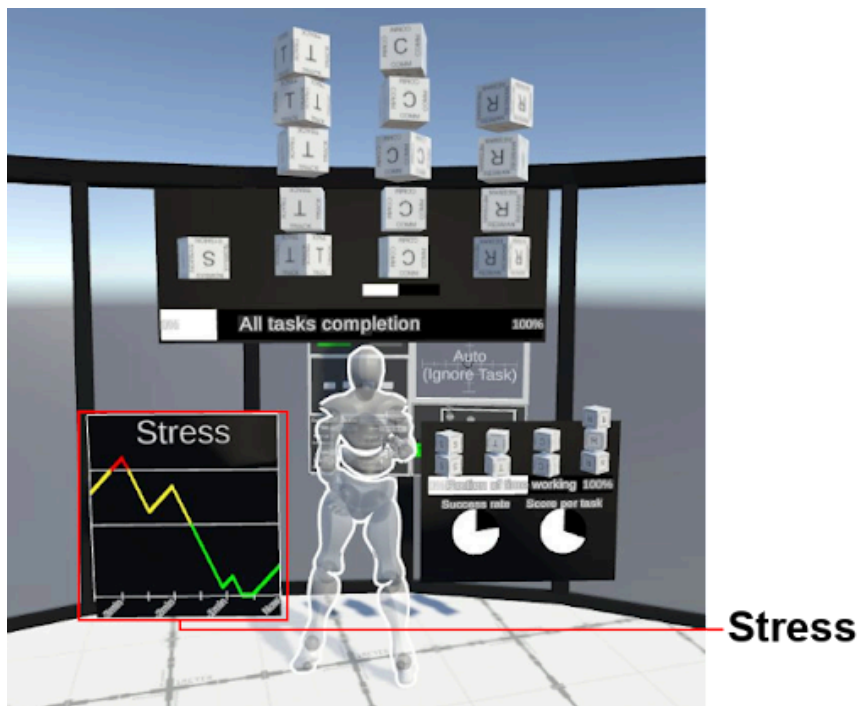
Not Clearly identified all of them

Skip to question 47

Component assessment (Symbolic - Stress)

You have been asked to get all tasks done as quickly as possible while maximizing the success rate of the tasks.

36. Did the stress feedback help? *

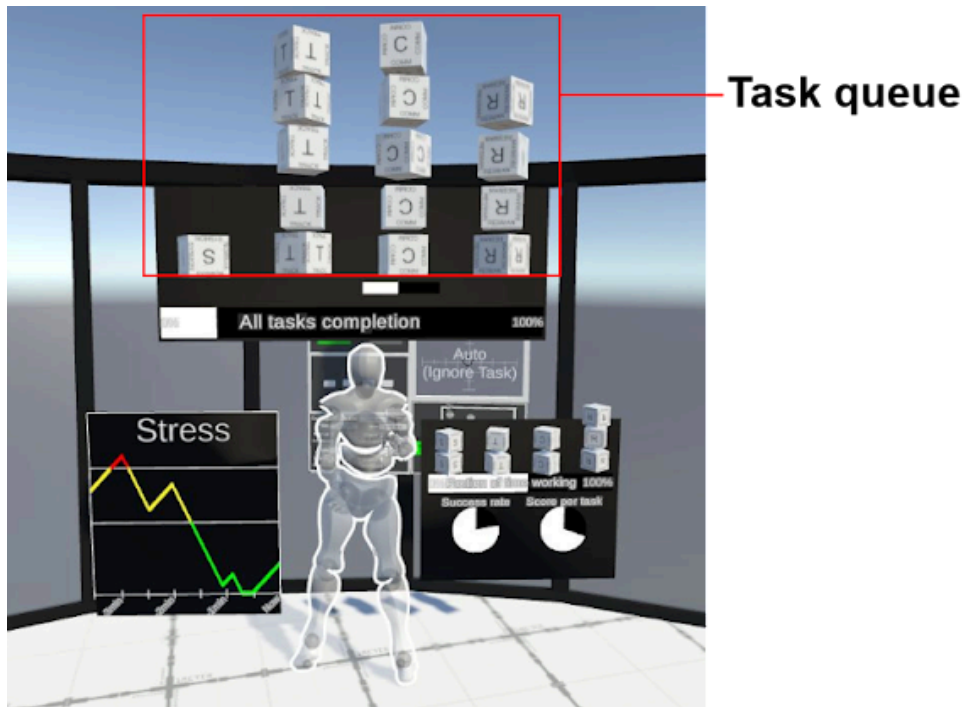


Mark only one oval.

1 2 3 4 5

Not A lot

37. Did the task queue feedback help? *

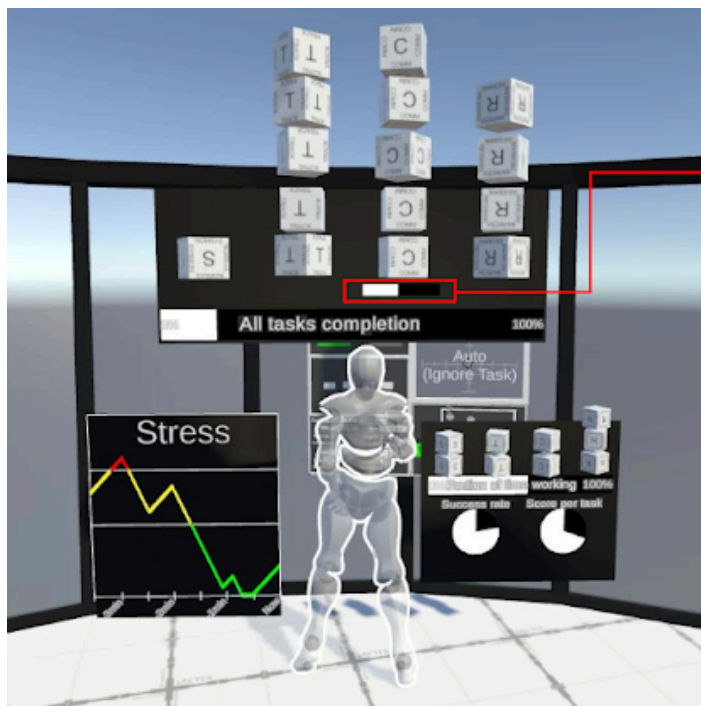


Mark only one oval.

1 2 3 4 5

Not A lot

38. Did the completion of current task feedback help? *



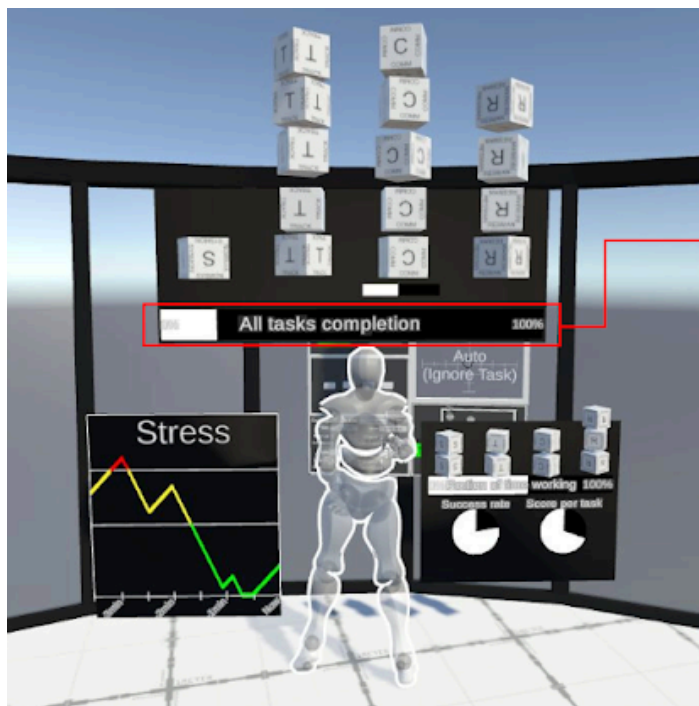
Current task completion

Mark only one oval.

1 2 3 4 5

Not A lot

39. Did the completion of all tasks feedback help? *



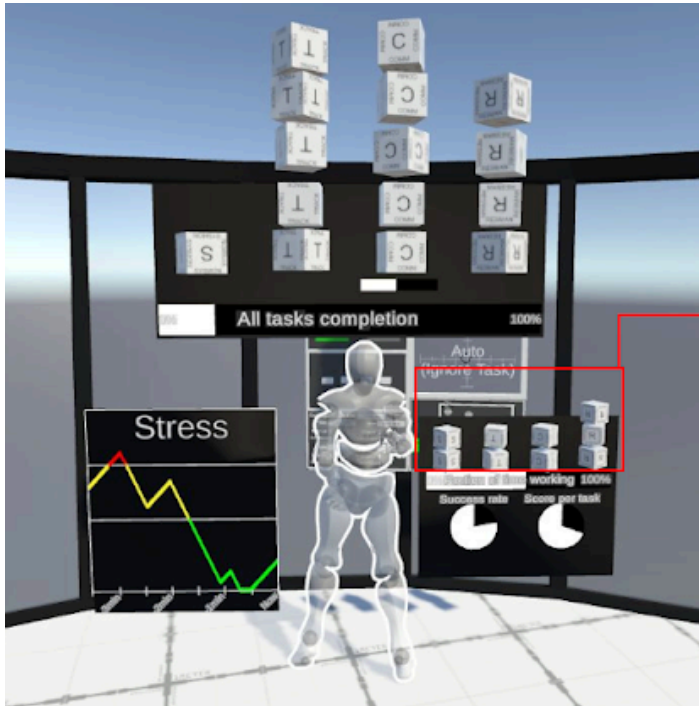
All tasks completion

Mark only one oval.

1 2 3 4 5

Not A lot

40. Did the task history help? *



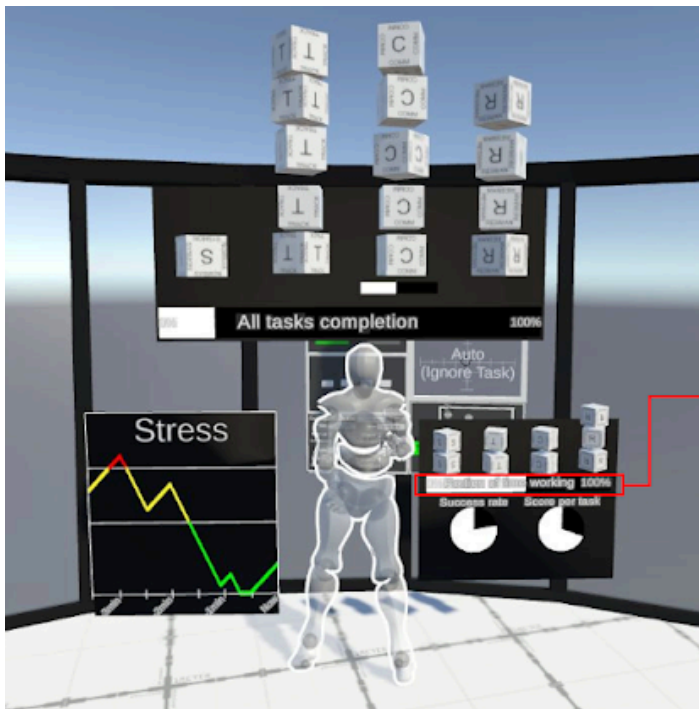
Task history

Mark only one oval.

1 2 3 4 5

Not A lot

41. Did the feedback on the portion of time passed working help? *



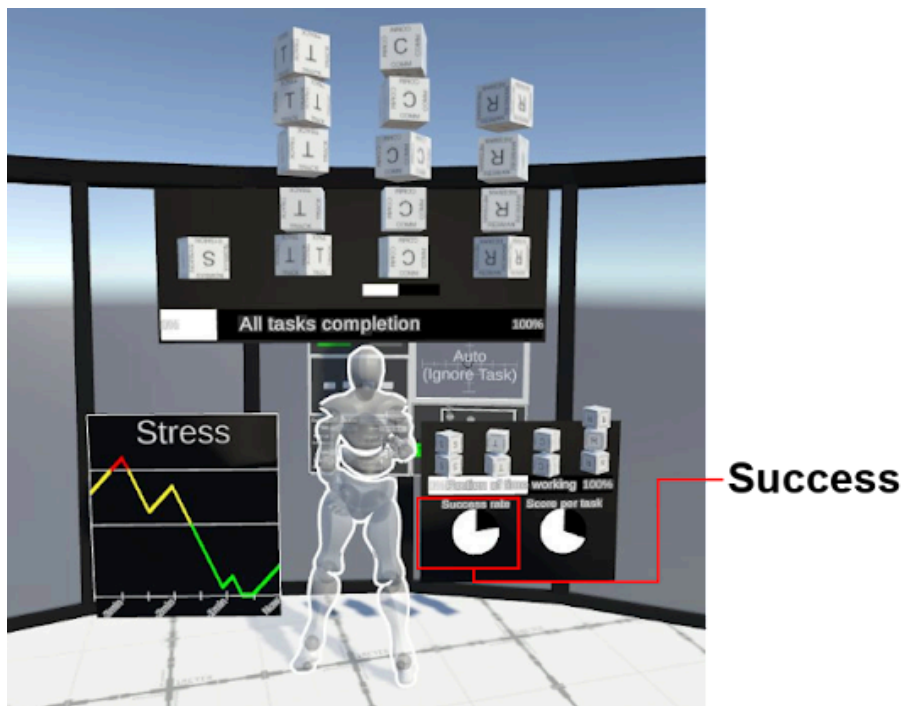
Portion of time working

Mark only one oval.

1 2 3 4 5

Not A lot

42. Did the Success/Failure feedback help? *

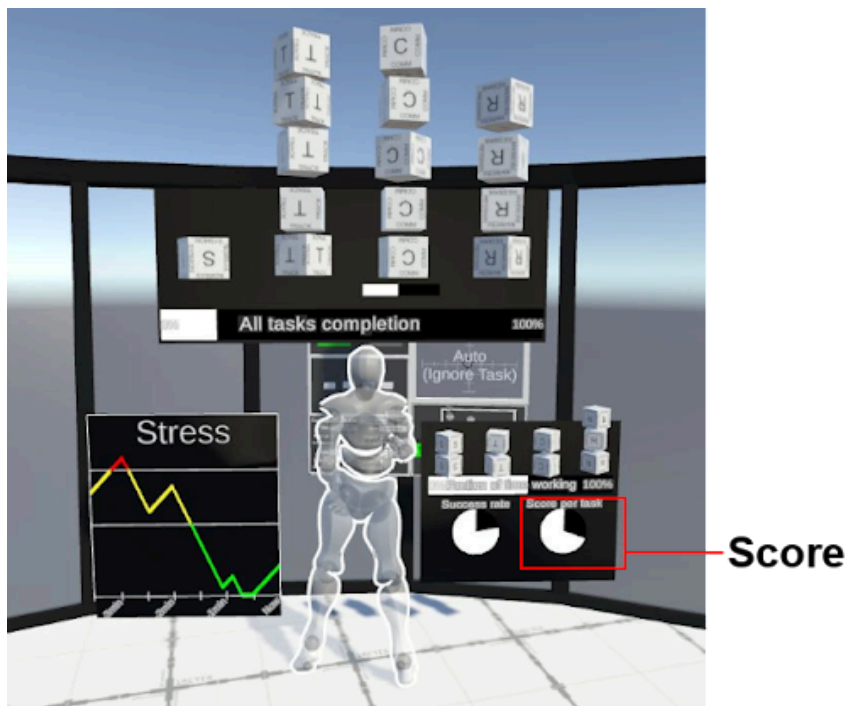


Mark only one oval.

1 2 3 4 5

Not A lot

43. Did the Score feedback help? *



Mark only one oval.

1 2 3 4 5

Not A lot

45. What strategy did you use to dispatch tasks? *

46. Did you manage to identify the slow and fast operators ? *

There were 2 fast operators, 2 medium speed operators and 2 slow operators.

Mark only one oval.

1 2 3 4 5

Not Clearly identified all of them

Skip to question 47

NASA Task Load Index

47. Mental Demand - How mentally demanding was the task? *

How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

Mark only one oval.

1 2 3 4 5

Very Very High

48. Physical Demand - How physically demanding was the task? *

How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Mark only one oval.

1 2 3 4 5

Very Very High

49. Temporal Demand - How hurried or rushed was the pace of the task? *

How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely, or rapid and frantic?

Mark only one oval.

1 2 3 4 5

Very Very High

50. Performance - How successful were you in accomplishing what you were asked to do? *

How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

Mark only one oval.

1 2 3 4 5

Perf Failure

51. Effort - How hard did you have to work to accomplish your level of performance? *

How hard did you have to work (mentally and physically) to accomplish your level of performance?

Mark only one oval.

1 2 3 4 5

Very Very High

52. Frustration - How insecure, discouraged, irritated, stressed, and annoyed were you? *

How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Mark only one oval.

1 2 3 4 5

Very Very High

Skip to question 53

53. I think that I would like to use this system frequently. *

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

54. I found the system to be simple. *

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

55. I thought the system was easy to use. *

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

56. I think that I could use this system without the support of a technical person. *

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

57. I found the various functions in this system were well integrated. *

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

58. I thought there was a lot of consistency in this system. *

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

59. I would imagine that most people would learn to use this system very quickly. *

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

60. I found the system very intuitive. *

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

61. I felt very confident using the system. *

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

62. I could use this system without having to learn anything new. *

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

End of experiment questionnaire

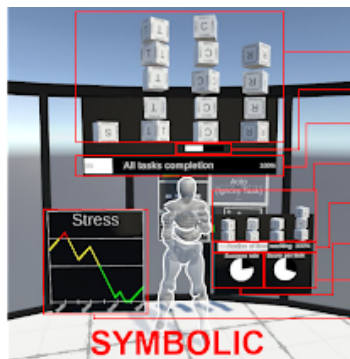
* Indicates required question

1. Participant ID *

2. For each component, choose in which condition you found it most useful. *



Task queue
 Current task completion
 All tasks completion
 Task history
 Portion of time working
 Success
 Score
 Stress



Task queue
 Current task completion
 All tasks completion
 Task history
 Portion of time working
 Success
 Score
 Stress

Mark only one oval per row.

	Literal without Stress	Literal with Stress	Symbolic without Stress	Symbolic with Stress
Task queue	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Current task completion	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
All tasks completion	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Task history	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Portion of time working	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Success / Failure	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Score	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Stress	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

3. Did you change your strategy to assign tasks when you changed condition? Explain why. *

4. Do you think it is important to have feedback on the stress level of operators? Explain why. *

5. Did you check that a highly stressed operator would likely fail their tasks? *

Mark only one oval.

No

Yes

6. What did you prefer with the Literal condition? *

7. What did you prefer with the Symbolic condition? *

8. If you could make combinations of Literal and Symbolic visualizations of the same component, which one(s) would you make? *

9. Any more remarks ?

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Chapter 5

Likewise, the first appendix is the ethics committee approval for the study presented in Chapter 5. It is followed by the participant information sheet, consent form and questionnaires used for this study. Several plots of the data analysed in this chapter are also available after these documents.

RE: 204935 - Project variation - APPROVED

Human Ethics <humanethics@unisa.edu.au>

Mon 29/05/2023 08:42

To: Rinnert, Thomas Jean-Noel, Hubert, Rene-Marc - rinty003 <thomas.rinnert@mymail.unisa.edu.au>
Cc: Bruce Thomas <Bruce.Thomas@unisa.edu.au>; James Walsh <James.Walsh@unisa.edu.au>

Dear Thomas,

RE: Amendment to Ethics Protocol 204935 "Comparative study of user status representation within a collaborative virtual environment" (E1 approved 20/09/2022 to 20/09/2025)

Thank you for submitting a Project Variation Request relating to the above project. I am pleased to advise that the Chairperson of the University's Human Research Ethics Committee has reviewed and approved the following:

- Update to the visual indicators displayed in the virtual environment that participants are interacting with (to emphasise the stress feedback of virtual workers).

Please regard this email as formal notification of approval.

Ethics approval is always made on the basis of a number of conditions outlined in the 'HREC Conditions of Approval' document found at: <https://i.unisa.edu.au/siteassets/staff/unisa-ro/docs/unisa-hrec-standard-conditions-of-approval-28-march-2023.pdf>; it is important that you are familiar with, and abide by, these conditions. It is also essential that you conduct all research according to UniSA guidelines, which can be found at: <https://i.unisa.edu.au/staff/research/research-ethics/human-research-ethics/ethics-policies-guidelines/>.

Thank you once again and best wishes for the project.

Many thanks,
Alex

Alex Osis | Human Ethics Officer | UniSA Research Office
University of South Australia | Enterprise Hub | City West Campus
Ph: 08 830 29199 | Email : humanethics@unisa.edu.au
Website: [Welcome to UniSA Research Office](#)

Please note my work days are Mon, Tues, Thurs and Fri



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From: Rinnert, Thomas Jean-Noel, Hubert, Rene-Marc - rinty003 <thomas.rinnert@mymail.unisa.edu.au>
Sent: Tuesday, 23 May 2023 1:59 PM
To: Human Ethics <humanethics@unisa.edu.au>
Cc: Bruce Thomas <Bruce.Thomas@unisa.edu.au>; James Walsh <James.Walsh@unisa.edu.au>
Subject: 204935 - Project variation

Dear Committee,

I want to pursue my research with another experiment that is very similar to the previous one. I've attached the project variation form to this email.

If you need more information, I'll be happy to provide it.

Yours,

Thomas RINNERT
PhD Student.



University of
South Australia
STEM Academic Unit

Participant Information Sheet

Title	Comparative study of user status representation within a collaborative virtual environment
Project Number	204935
Chief Investigator/ Principal Investigator	Thomas Rinnert
Supervisor	Bruce Thomas & James Walsh

Participation in this research is voluntary. If you don't wish to take part, you don't have to. If you decide you want to take part in the research project, you will be asked to sign the consent section. By signing it you are telling us that you:

- Understand what you have read
- Consent to take part in the research project
- Consent to the use of your information as described.

If you later change your mind, you are free to withdraw from the project at any stage and, if you wish, your data will be destroyed.

We want to investigate how to improve collaborative awareness: awareness of each other within a collaborative virtual environment, focusing on sharing each other's progress. We are interested in scenarios where a supervisor has to manage the workload of a team. The goal of this study is to better understand how sharing user status can improve collaborative awareness and task performance.

If you agree to participate in this study, you will be escorted from the lobby of Building W on UniSA's Mawson Lakes campus to the room where the experiment takes place (W1-17). You will participate in an experiment of about one hour during which you will be asked to distribute tasks to virtual operators using an immersive headset and its controllers (HTC Vive Cosmos).

The virtual operators will face an interface to perform tasks. You will receive tasks to assign to operators, these tasks will be represented by cubes on which the name of the associated task will be written. The operators will each have a task queue to execute, each task will increase their stress level. The higher the stress level of an operator, the more likely he is to fail at his task. Finally, not all operators perform their tasks at the same speed.

We will record your choices of task assignment to operators, the number of tasks successfully completed by each operator and the time required for the team to complete all tasks. During the experiment, several visual aids will be proposed to you, between each trial, you will fill a questionnaire to rate them, at the end you'll be asked to compare them.

On top of contributing to the research and gaining knowledge on the subject of human-computer interaction, you will be compensated for your time with a \$20 gift card.

What are the possible risks and disadvantages of taking part?

Given the current situation (Covid-19), this experiment will strictly adhere to the health protocol defined within UniSA.

There is a risk that some susceptible participants may experience some of the symptoms of simulator sickness similar to those associated with motion sickness: discomfort, headache, stomach ache, nausea, vomiting, paleness, sweating, fatigue, drowsiness, disorientation, apathy. These symptoms generally occur gradually, are easily detectable by the subject and are quickly resolved after the end of the immersive experience. The complete recovery of the most important symptoms is generally reached after a rest period of 15 to 20 minutes. The last phase of the experience will be extended as much as necessary in order to guarantee your safety whatever the post-experimental activity envisaged (walking, cycling, driving ...). The tests are in 3D and this could possibly cause visual fatigue, but their nature and duration have been designed to minimise this risk as much as possible.

What will happen to information about me?

Each participant will be assigned a unique identifier that will preserve his or her anonymity. The data captured automatically during the experiment will be linked to this unique identifier and cannot be directly linked to your identity. The only personal data (Name and First name), will be kept in paper format in a secure place in order to guarantee your rights of retraction and rectification, only the scientific leader and the assistant researchers will have access to it. Age and gender information may be used for statistics on all participants. The identity of the participants will not be used or communicated under any circumstances. In accordance with the provisions of the French Data Protection Act and the Australian Code for the Responsible Conduct of Research, you may exercise your right to access, rectify or delete data concerning you by simply requesting the project's scientific manager. The results of this research may be presented in scientific conferences and published in conference proceedings or in a journal, you can have access to them by contacting the scientific manager.

Research contact person

Name	Thomas Rinnert
Position	PhD student
Telephone	0410 638 954
Email	thomas.rinnert@mymail.unisa.edu.au

The ethical aspects of this research project have been approved by the Human Research Ethics Committee (HREC) of the University of South Australia as required by the Australian government research requirements, specified in the National Statement on Ethical Conduct in Human Research (2007 - updated 2018). This statement has been developed to protect the interests of people who agree to participate in human research studies. If you have any complaints about any aspect of the project, the way it is being conducted or any questions about being a research participant in general, please contact:

Reviewing HREC name	University of South Australia Human Research Ethics Committee
HREC Executive Officer	Human Ethics Officer
Telephone	+618 8302 6330
Email	humanethics@unisa.edu.au

Reviewing HREC approving this research and HREC Executive Officer details



This project has been approved by the University of South Australia's Human Research Ethics Committee. If you have any ethical concerns about the project, or questions about your rights as a participant, please contact the Executive Officer of this Committee, Tel: +61 8 8302 6330; Email: humanethics@unisa.edu.au

SECTION 1: CONTACT AND PROJECT DETAILS

Researcher's Full Name	Thomas Rinnert
Contact Details	thomas.rinnert@mymail.unisa.edu.au
Supervisor's Name <i>(students only)</i>	Prof Bruce Thomas, Dr James Walsh
Contact Details	{bruce.thomas, james.walsh}@unisa.edu.au
Project Number	204935
Project Title	Comparative study of user status representation within a collaborative virtual environment

SECTION 2: PARTICIPANT CERTIFICATION

In signing this form, I confirm that:

- I have read the Participant Information Sheet, and the nature and the purpose of the research project has been explained to me. I understand and agree to take part.
- I understand the nature of my involvement in the project.
- I understand that I may not directly benefit from taking part in the project.
- I understand that I can withdraw from the project at any stage and that this will not affect my status now or in the future.
- I am over 18 years of age.
- I understand that while information gained during the project may be published, I will not be identified and my personal results will remain confidential, unless required by law.

- I understand that non-identifiable data collected from this project may be used for another purpose by the researcher and/or shared openly with other researchers for future research projects (for which ethics approval will be sought).

<i>Participant's Signature</i>	<i>Printed Name</i>	<i>Date</i>
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SECTION 3: RESEARCHER CERTIFICATION

I have explained the study to the participant and consider that he/she understand what is involved.

<i>Researcher Signature</i>	<i>Printed Name</i>	<i>Date</i>
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Demographic questionnaire

* Indicates required question

1. Participant ID *

2. Gender *

Mark only one oval.

Male

Female

Other:

3. Age *

4. You are *

Mark only one oval.

Left-handed

Ambidextrous

Right-handed

5. Are you used to video games? *

Mark only one oval.

1 2 3 4 5

Not A lot

6. Are you used to 3D environments? *

Mark only one oval.

1 2 3 4 5

Not A lot

7. Are you used to Immersive technologies? *

Mark only one oval.

1 2 3 4 5

Not A lot

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Condition assessment

First page to be filled by the experimenter

* Indicates required question

1. Participant ID *

2. Trial number *

Mark only one oval.

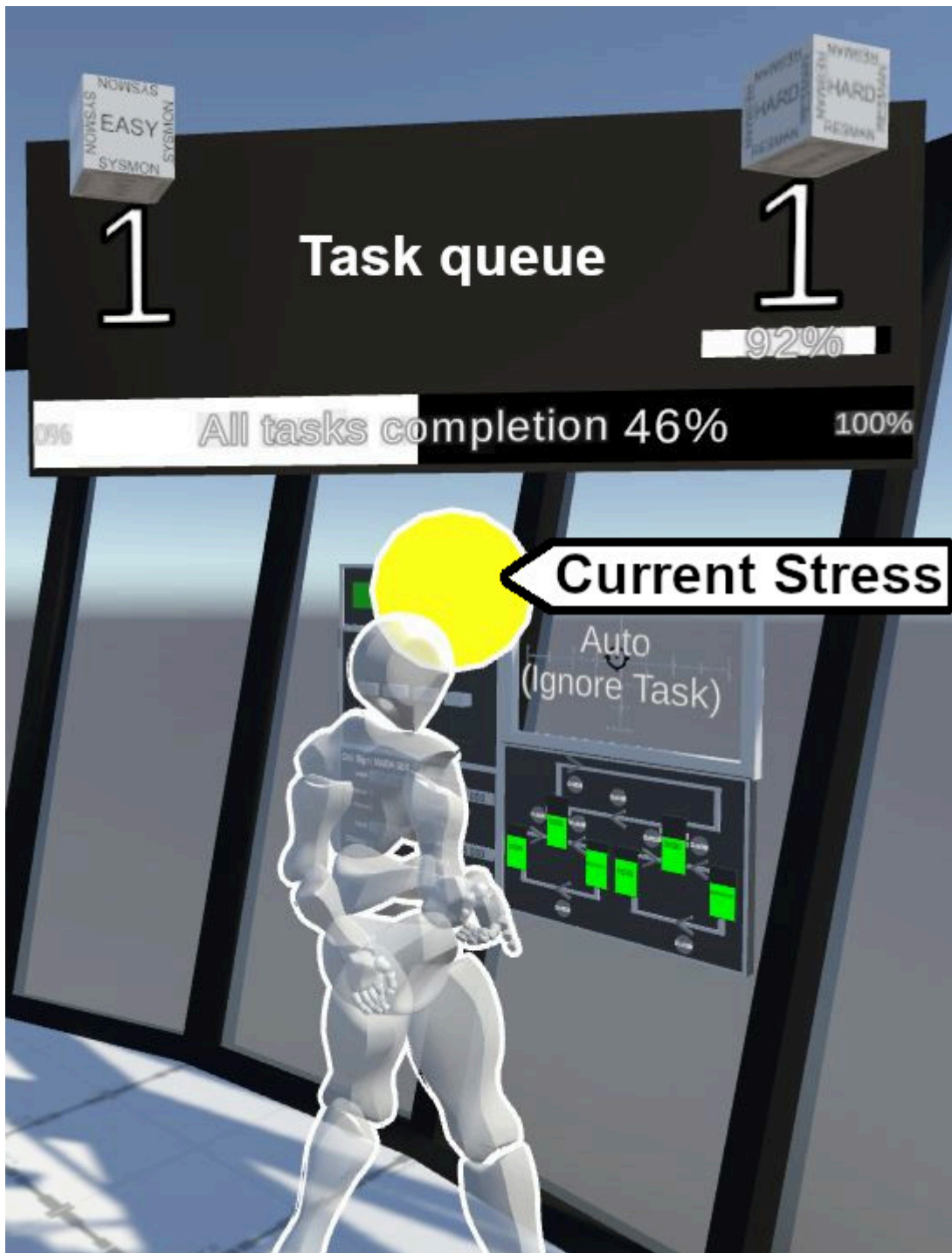
1 2 3 4

3. Condition *

Mark only one oval.

- C1: 3 Colors - No Prediction *Skip to question 4*
- C2: 5 Colors - No Prediction *Skip to question 8*
- C3: 3 Colors - With Prediction *Skip to question 12*
- C4: 5 Colors - With Prediction *Skip to question 18*

C1: 3 Colors - No Prediction



4. Did the **task queue** feedback help you to choose who to assign a task to? *

Mark only one oval.

1 2 3 4 5

Not A lot

5. Did the **current stress level** feedback help you to choose who to assign a task to? *

Mark only one oval.

1 2 3 4 5

Not A lot

6. What strategy did you use to dispatch tasks? *

7. Did you manage to identify the slow and fast operators ? *

There were 2 fast operators, 2 medium speed operators and 2 slow operators.

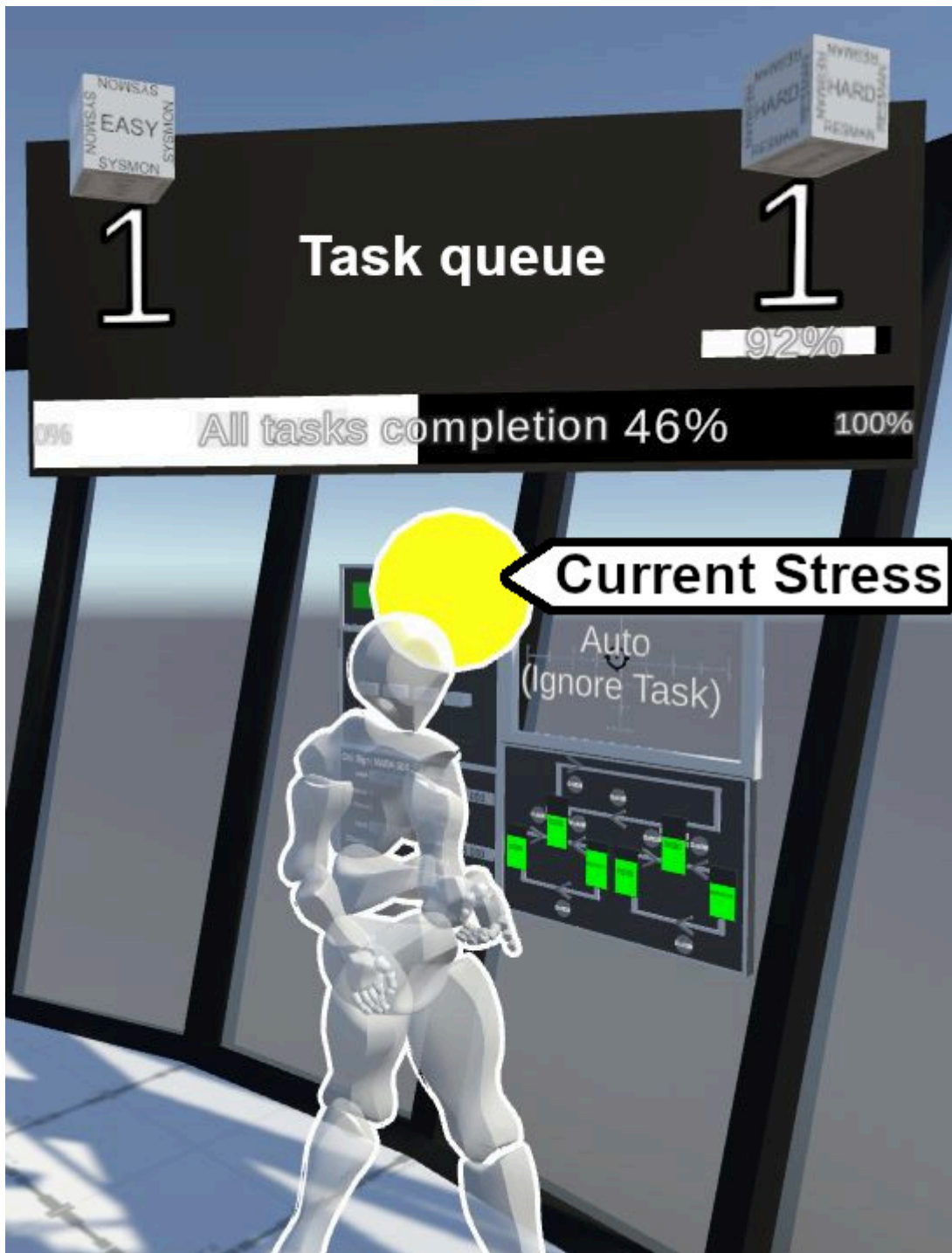
Mark only one oval.

1 2 3 4 5

Not Clearly identified all of them

Skip to question 24

C2: 5 Colors - No Prediction



8. Did the **task queue** feedback help you to choose who to assign a task to? *

Mark only one oval.

1 2 3 4 5

Not A lot

9. Did the **current stress level** feedback help you to choose who to assign a task to? *

Mark only one oval.

1 2 3 4 5

Not A lot

10. What strategy did you use to dispatch tasks? *

11. Did you manage to identify the slow and fast operators ? *

There were 2 fast operators, 2 medium speed operators and 2 slow operators.

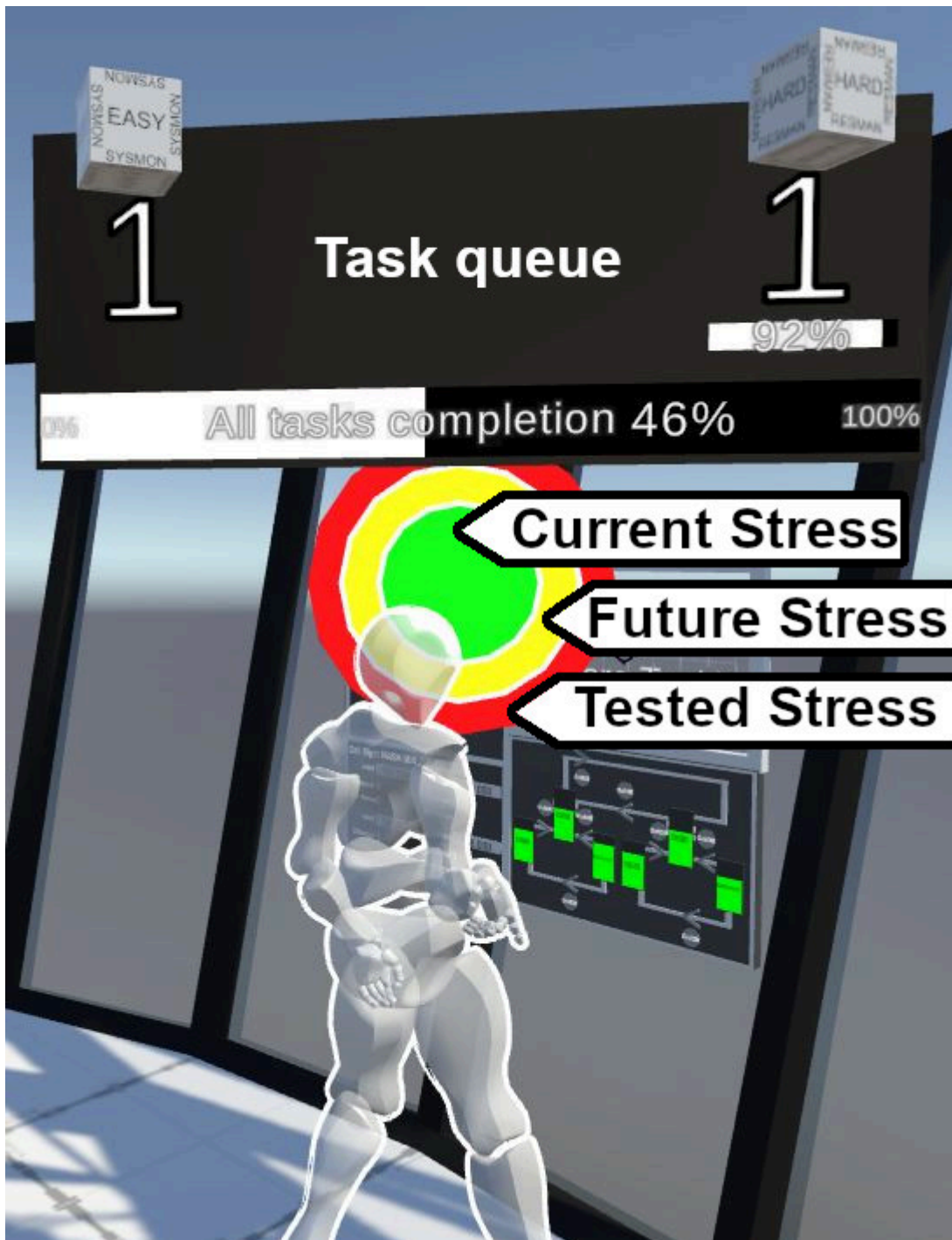
Mark only one oval.

1 2 3 4 5

Not Clearly identified all of them

Skip to question 24

C3: 3 Colors - With Prediction



12. Did the **task queue** feedback help you to choose who to assign a task to? *

Mark only one oval.

1 2 3 4 5

Not A lot

13. Did the **current stress level** feedback help you to choose who to assign a task to? *

Mark only one oval.

1 2 3 4 5

Not A lot

14. Did the **future stress level** feedback help you to choose who to assign a task to? *

Mark only one oval.

1 2 3 4 5

Not A lot

15. Did the **tested future stress level** feedback help you to choose who to assign a task to when you were having a task in hand? *

Mark only one oval.

1 2 3 4 5

Not A lot

16. What strategy did you use to dispatch tasks? *

17. Did you manage to identify the slow and fast operators ? *
- There were 2 fast operators, 2 medium speed operators and 2 slow operators.

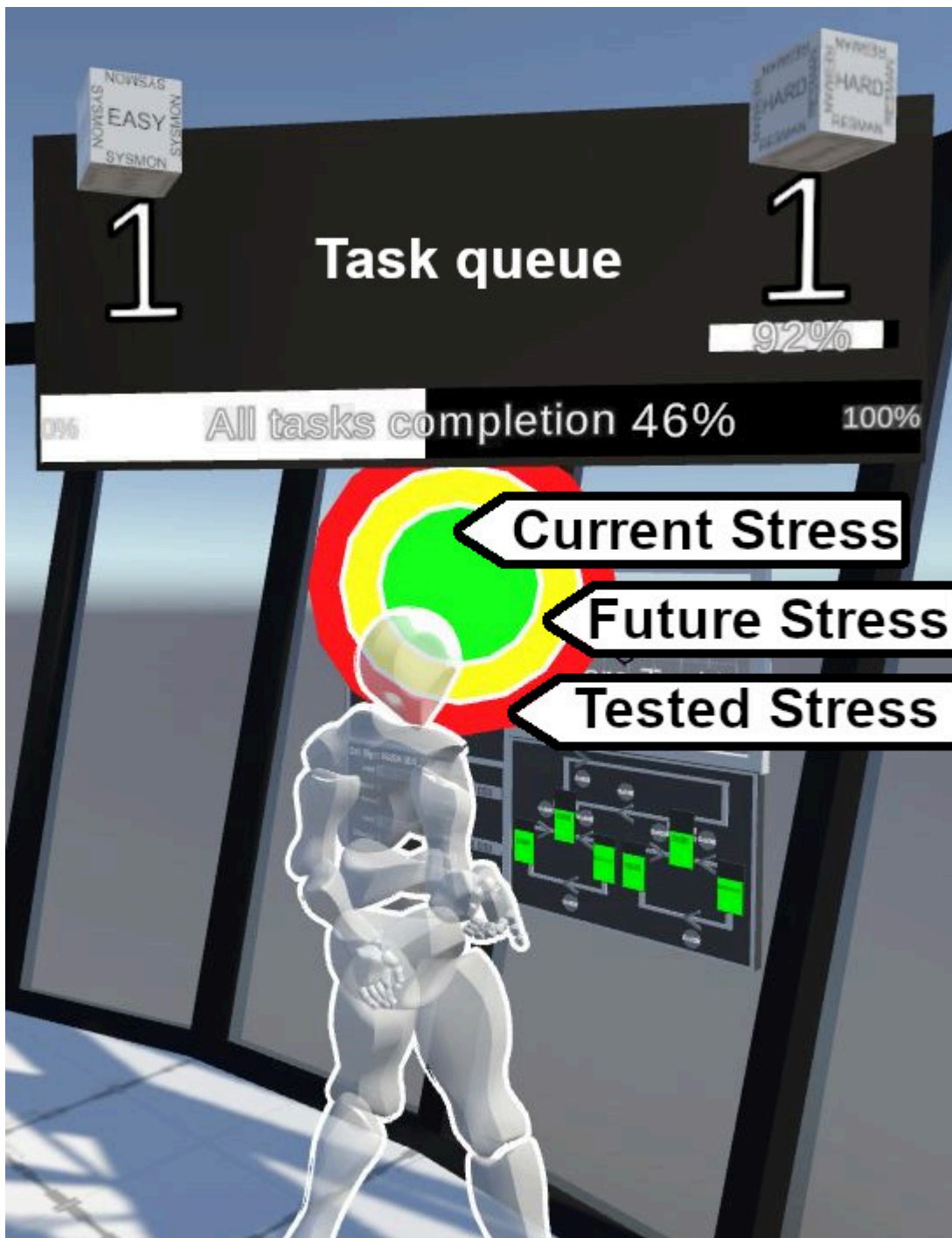
Mark only one oval.

1 2 3 4 5

Not Clearly identified all of them

Skip to question 24

C4: 5 Colors - With Prediction



18. Did the **task queue** feedback help you to choose who to assign a task to? *

Mark only one oval.

1 2 3 4 5

Not A lot

19. Did the **current stress level** feedback help you to choose who to assign a task to? *

Mark only one oval.

1 2 3 4 5

Not A lot

20. Did the **future stress level** feedback help you to choose who to assign a task to? *

Mark only one oval.

1 2 3 4 5

Not A lot

21. Did the **tested stress level** feedback help you to choose who to assign a task to? *

Mark only one oval.

1 2 3 4 5

Not A lot

22. What strategy did you use to dispatch tasks? *

23. Did you manage to identify the slow and fast operators ? *

There were 2 fast operators, 2 medium speed operators and 2 slow operators.

Mark only one oval.

1 2 3 4 5

Not Clearly identified all of them

Skip to question 24

NASA Task Load Index

24. Mental Demand - How mentally demanding was the task? *

How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

Mark only one oval.

1 2 3 4 5

Very Very High

25. Physical Demand - How physically demanding was the task? *

How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

Mark only one oval.

1 2 3 4 5

Very Very High

26. Temporal Demand - How hurried or rushed was the pace of the task? *

How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely, or rapid and frantic?

Mark only one oval.

1 2 3 4 5

Very Very High

27. Performance - How successful were you in accomplishing what you were asked to do? *
How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

Mark only one oval.

1 2 3 4 5

Perf Failure

28. Effort - How hard did you have to work to accomplish your level of performance? *
How hard did you have to work (mentally and physically) to accomplish your level of performance?

Mark only one oval.

1 2 3 4 5

Very Very High

29. Frustration - How insecure, discouraged, irritated, stressed, and annoyed were you? *
How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Mark only one oval.

1 2 3 4 5

Very Very High

Skip to question 30

System Usability Scale

30. I think that I would like to use this system frequently.

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

31. I found the system to be simple.

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

32. I thought the system was easy to use.

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

33. I think that I could use this system without the support of a technical person.

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

34. I found the various functions in this system were well integrated.

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

35. I thought there was a lot of consistency in this system.

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

36. I would imagine that most people would learn to use this system very quickly.

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

37. I found the system very intuitive.

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

38. I felt very confident using the system.

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

39. I could use this system without having to learn anything new.

Mark only one oval.

1 2 3 4 5

Stro Strongly agree

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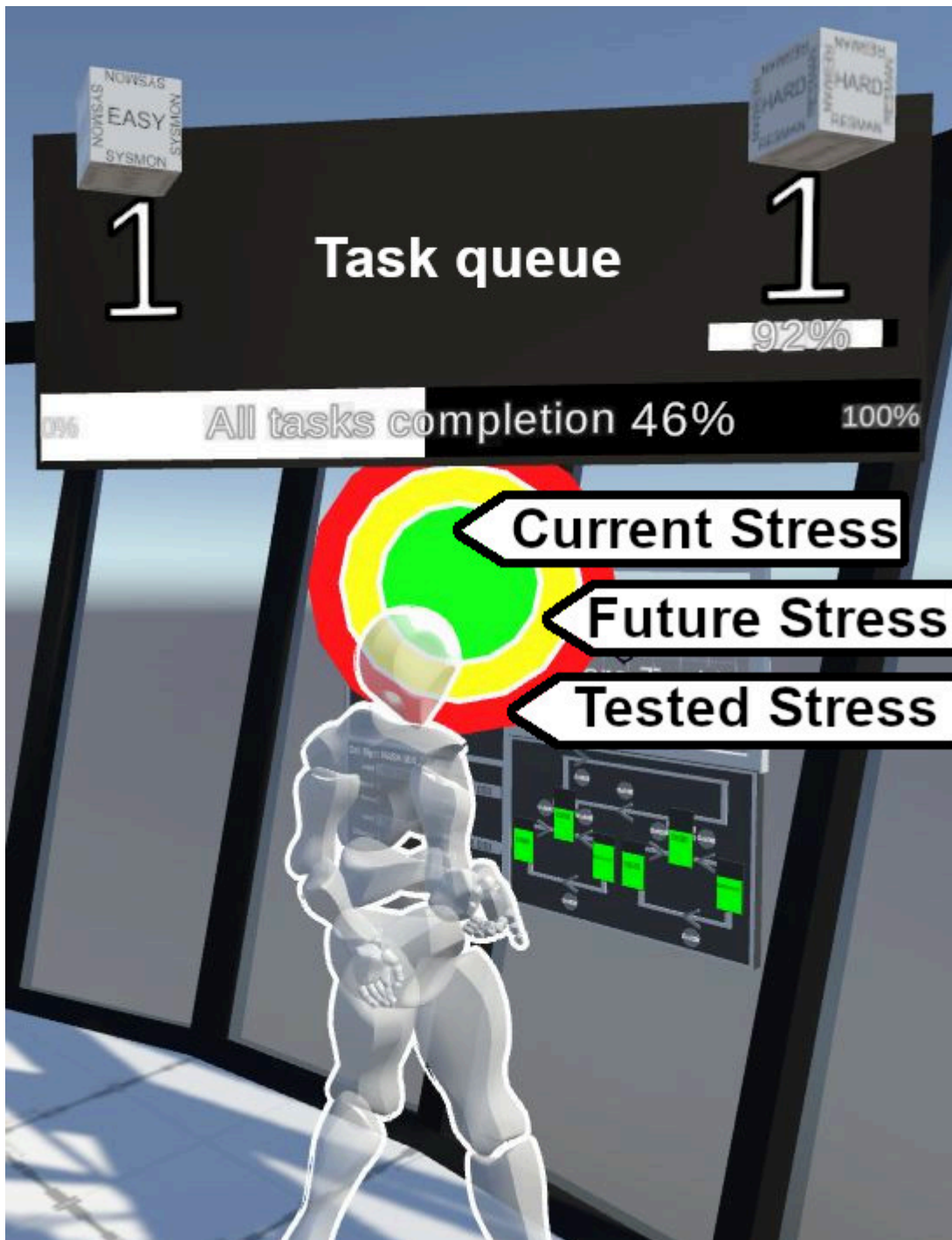
End of experiment questionnaire

* Indicates required question

1. Participant ID *

2. For the different stress feedbacks, did you change your strategy to assign tasks due to different visual stress feedback? Explain why. *

3. Regardless of the visual feedbacks, did you change your strategy to assign tasks across the experiment? Explain why. *

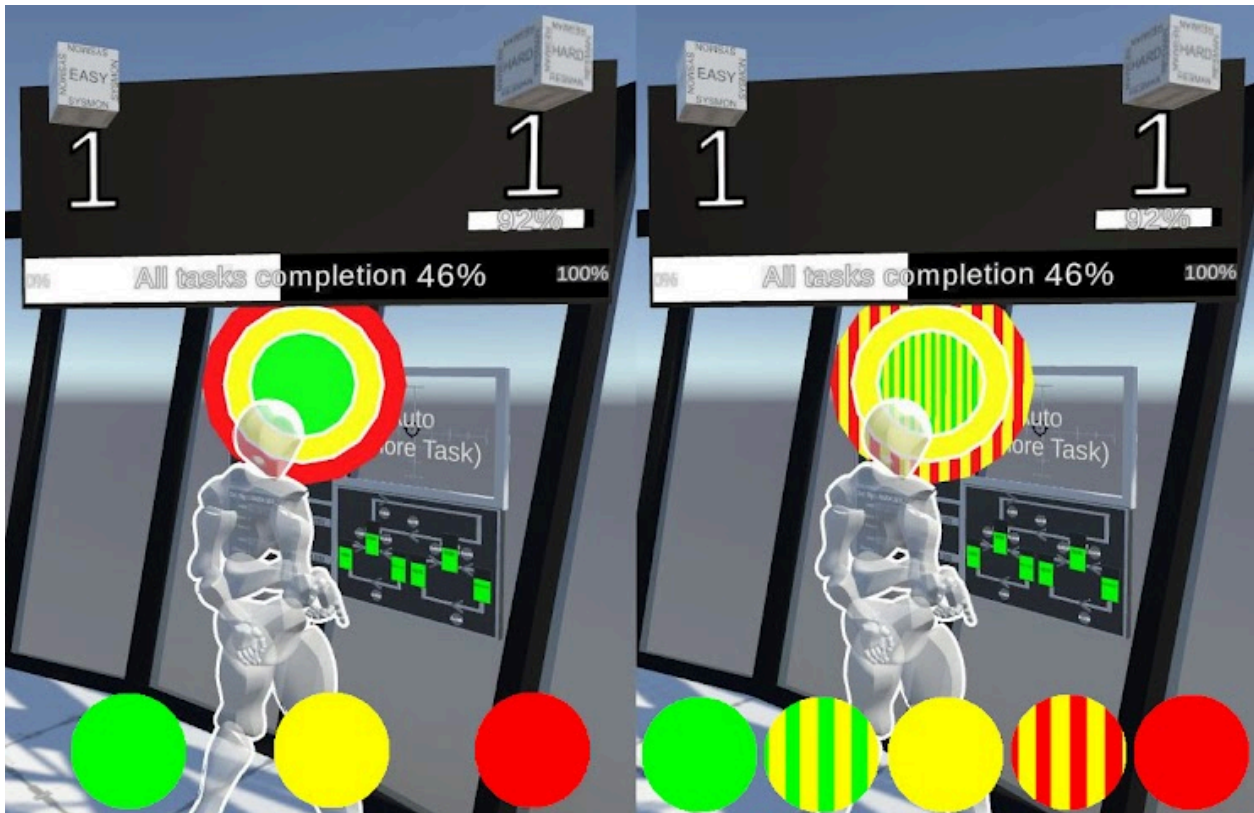


4. Do you think it is important to have feedback on the **current stress** level of operators? *
Explain why.

5. Do you think it is important to have feedback on the **future stress** level of operators? *
Explain why.

6. Do you think it is important to have feedback on the **tested future stress** level of operators? Explain why. *

7. Which did you prefer, having **3** or **5** different stress levels? *



Mark only one oval.

3 Levels (Left)

5 Levels (Right)

8. Any more remarks ?

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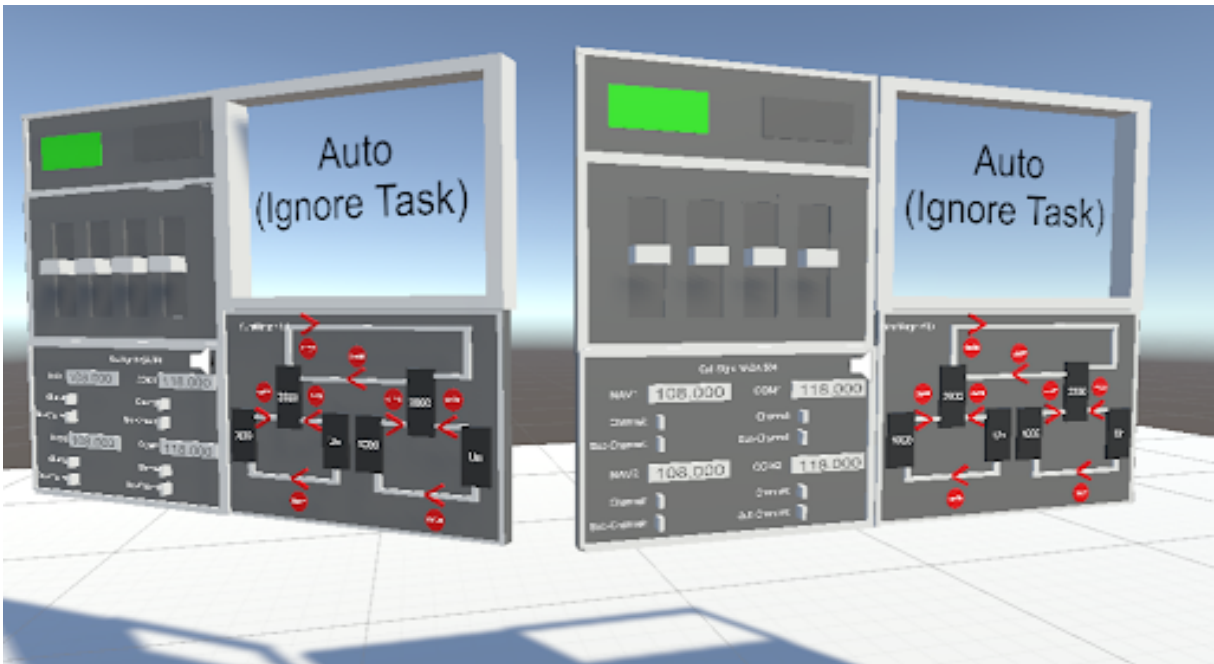


Figure 6.10 – Scene arrangement setting two MATB-II interfaces side by side with a large angle.

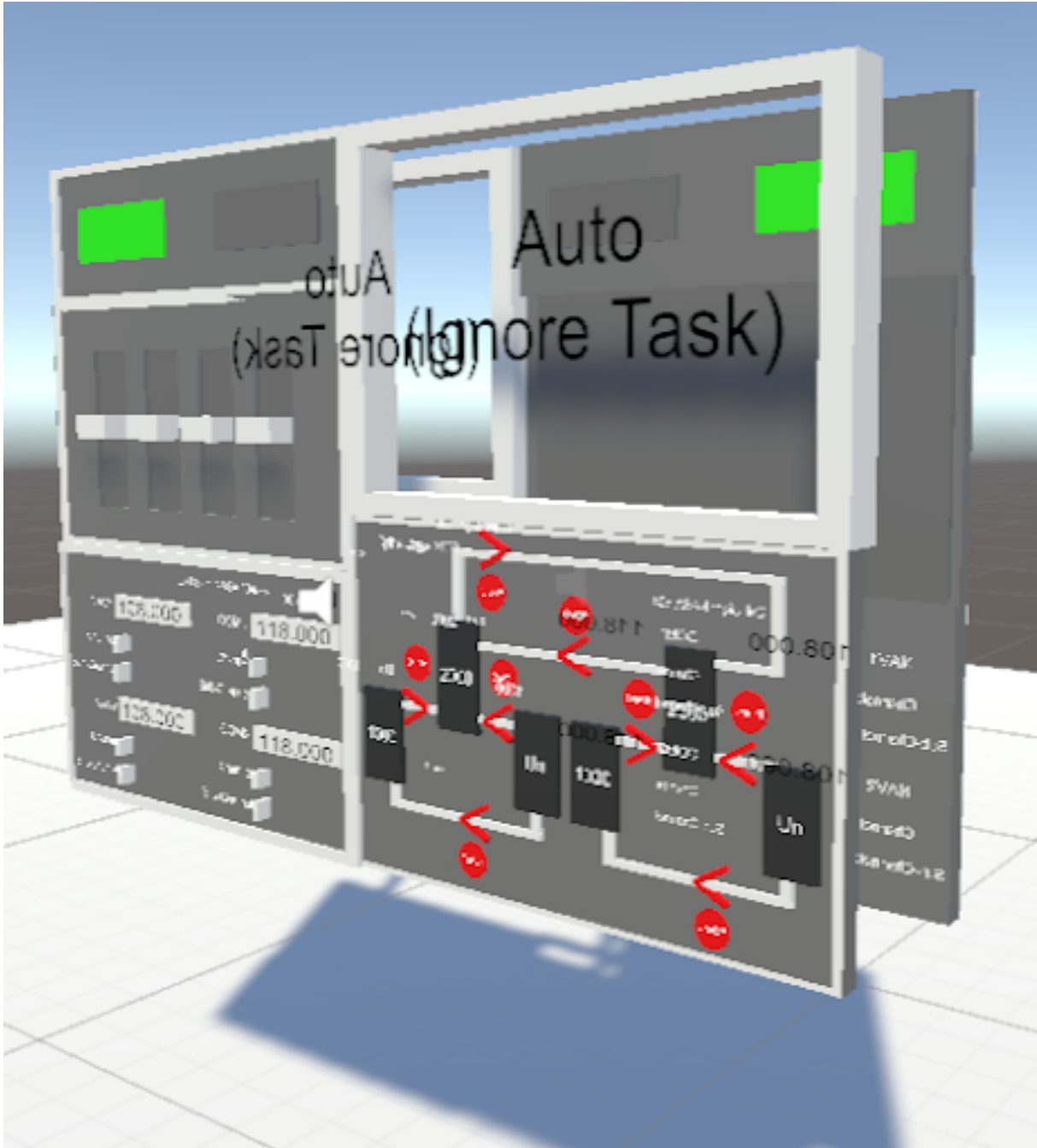
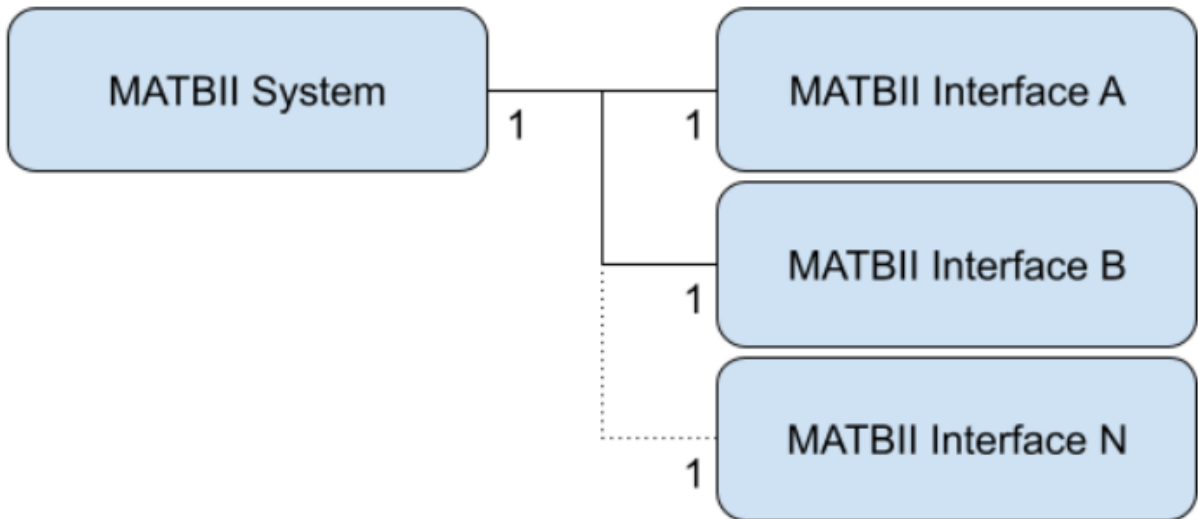


Figure 6.11 – Scene arrangement setting two MATB-II interfaces back to back.

Multiple interfaces
one common system for all users



one system for each user/interface

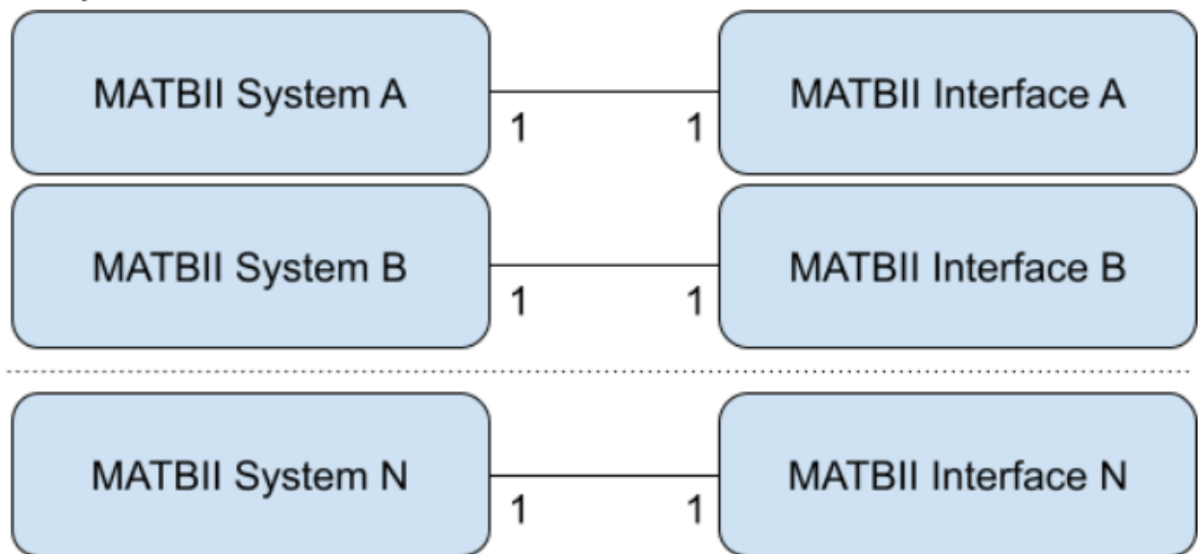


Figure 6.12 – On top: Multiple MATB-II interfaces displaying a single system status. At the bottom: Multiple MATB-II interfaces each displaying an independent system status.

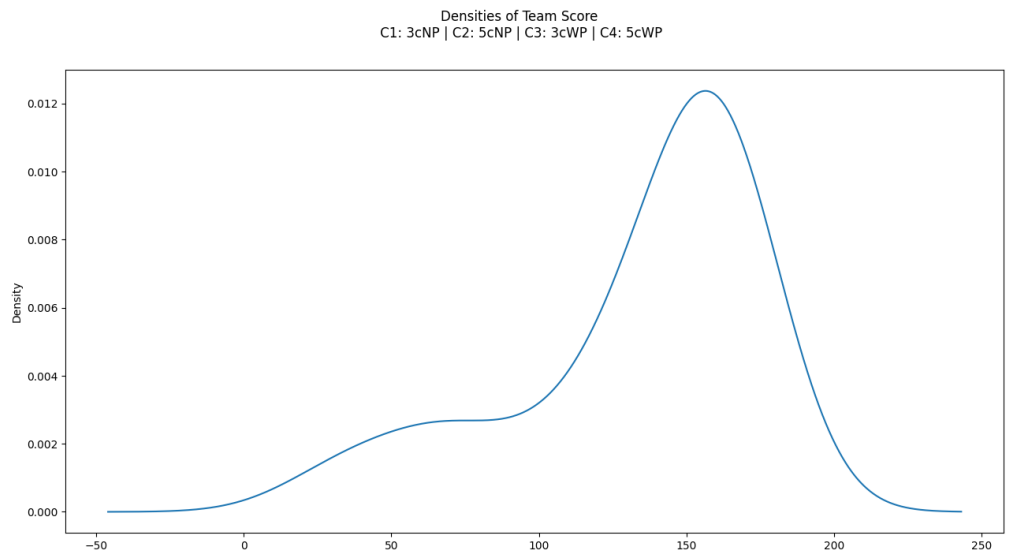


Figure 6.13 – Repartition of Team Score from the user study presented in Chapter 5.

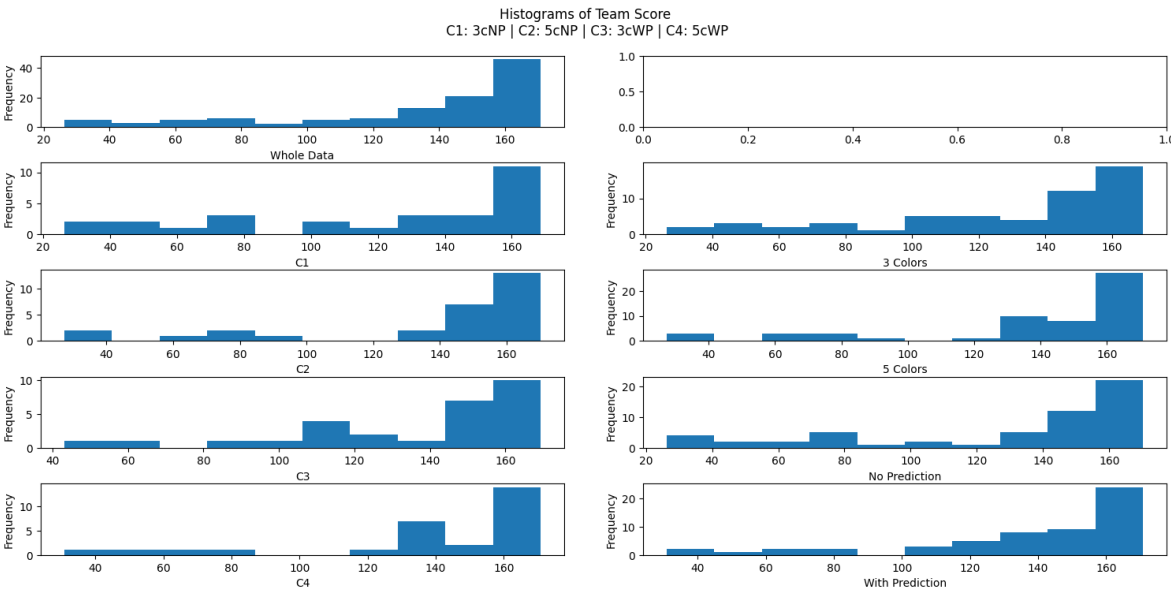


Figure 6.14 – Repartition of Team Score among conditions from the user study presented in Chapter 5.

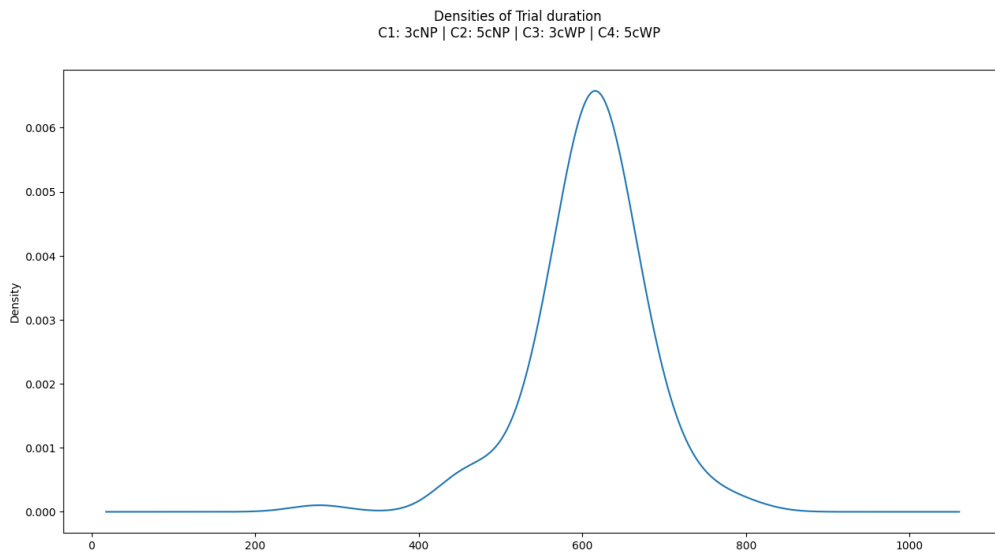


Figure 6.15 – Repartition of Trial duration from the user study presented in Chapter 5.

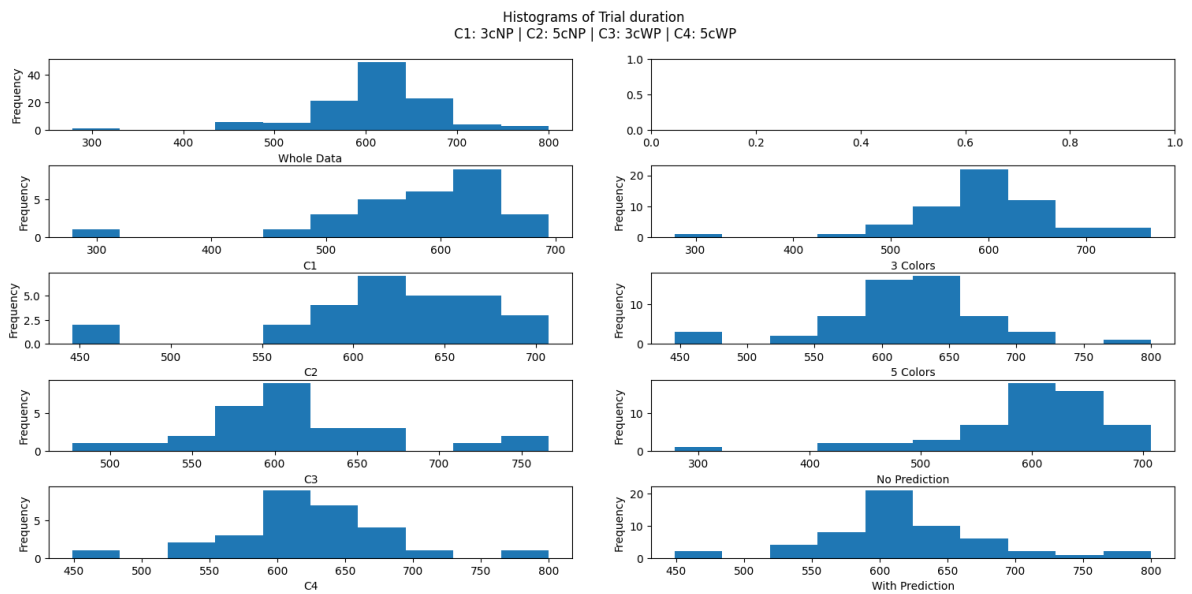


Figure 6.16 – Repartition of Trial duration among conditions from the user study presented in Chapter 5.

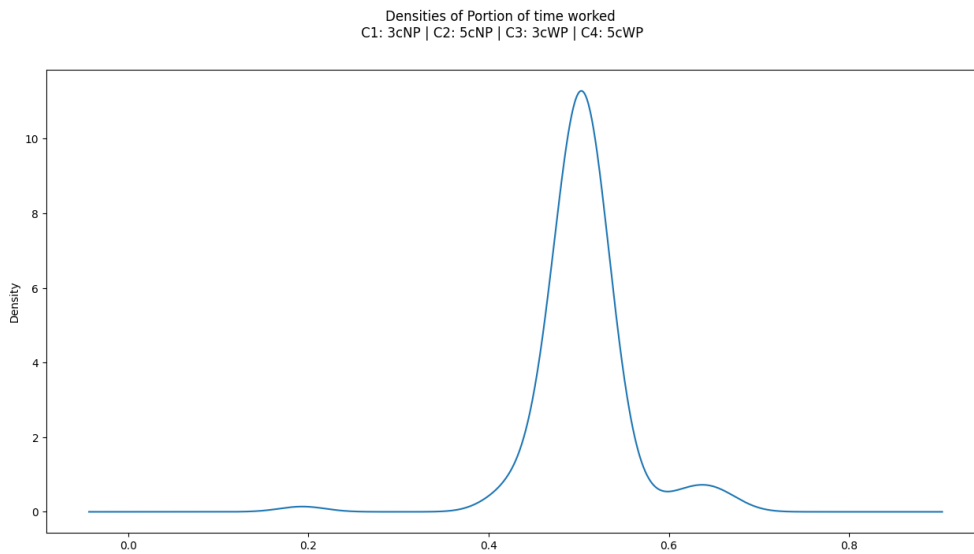


Figure 6.17 – Repartition of Portion of time worked from the user study presented in Chapter 5.

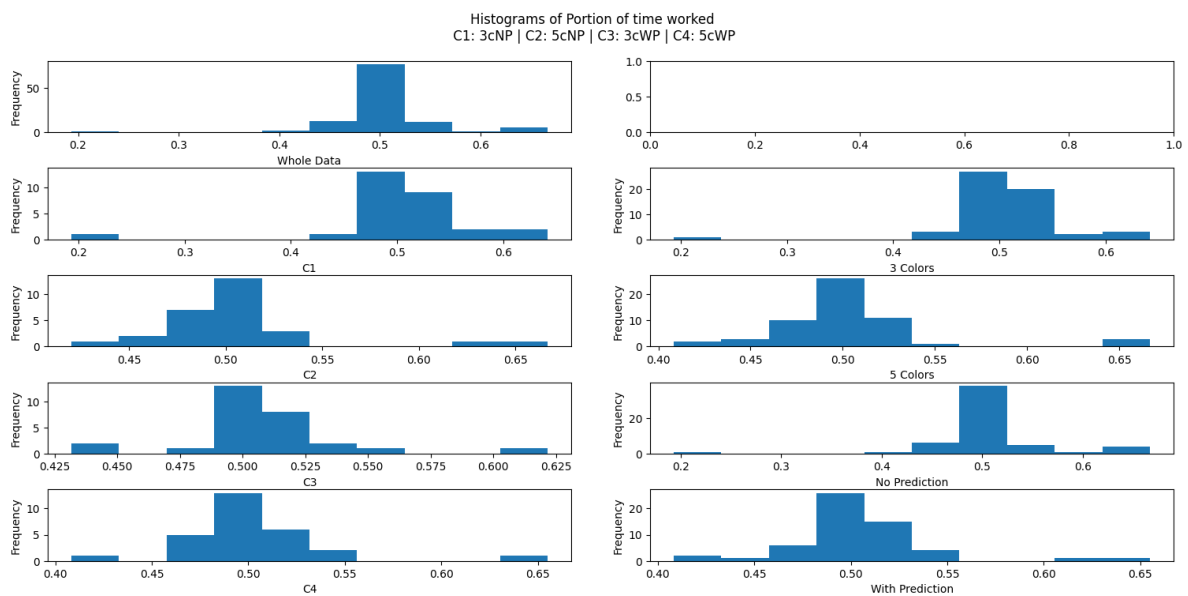


Figure 6.18 – Repartition of Portion of time worked among conditions from the user study presented in Chapter 5.

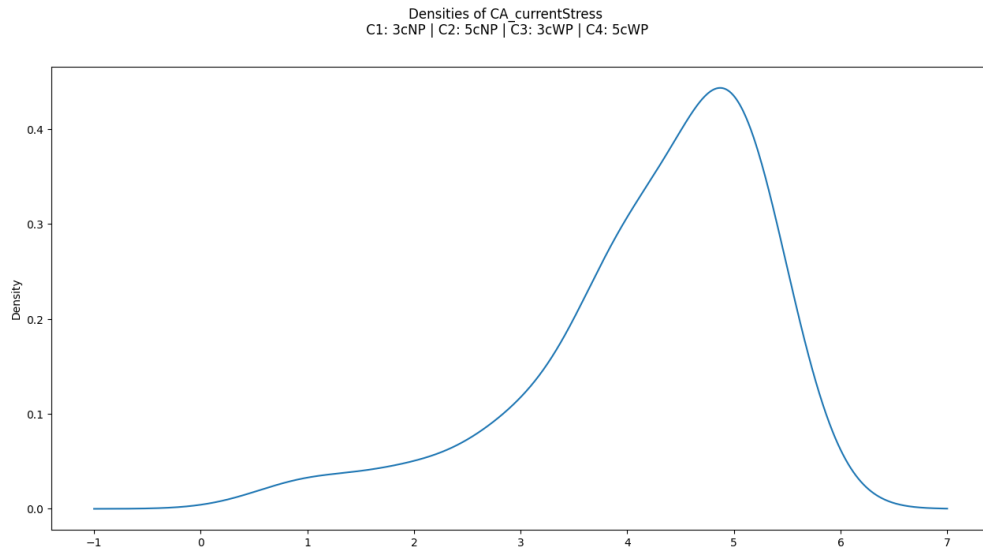


Figure 6.19 – Repartition of Current Stress from the user study presented in Chapter 5.

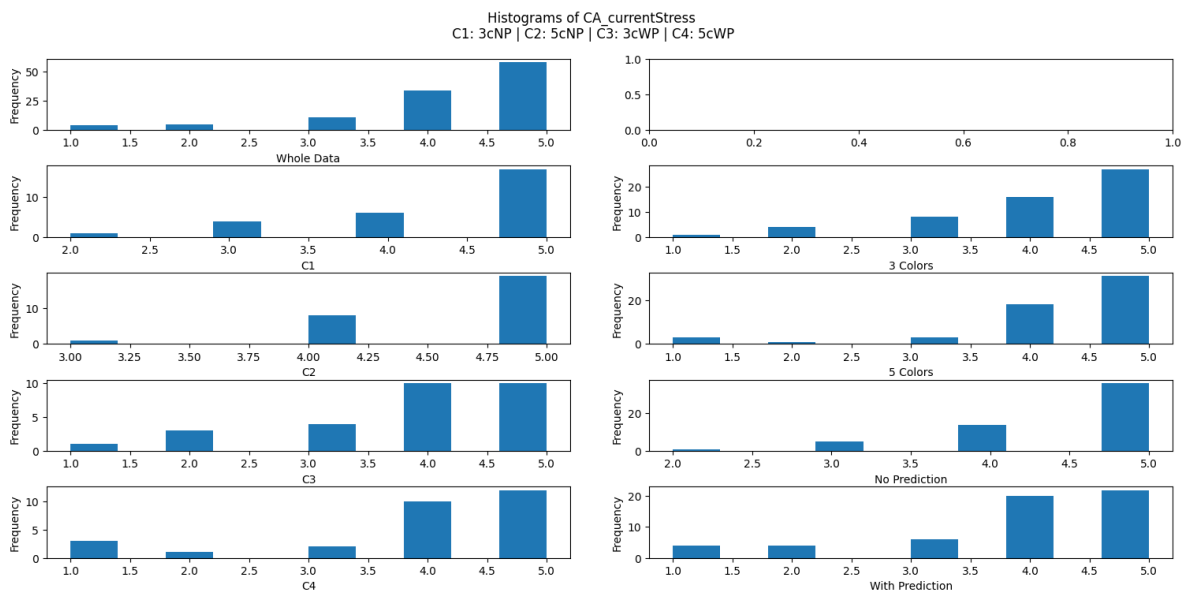


Figure 6.20 – Repartition of Current Stress among conditions from the user study presented in Chapter 5.

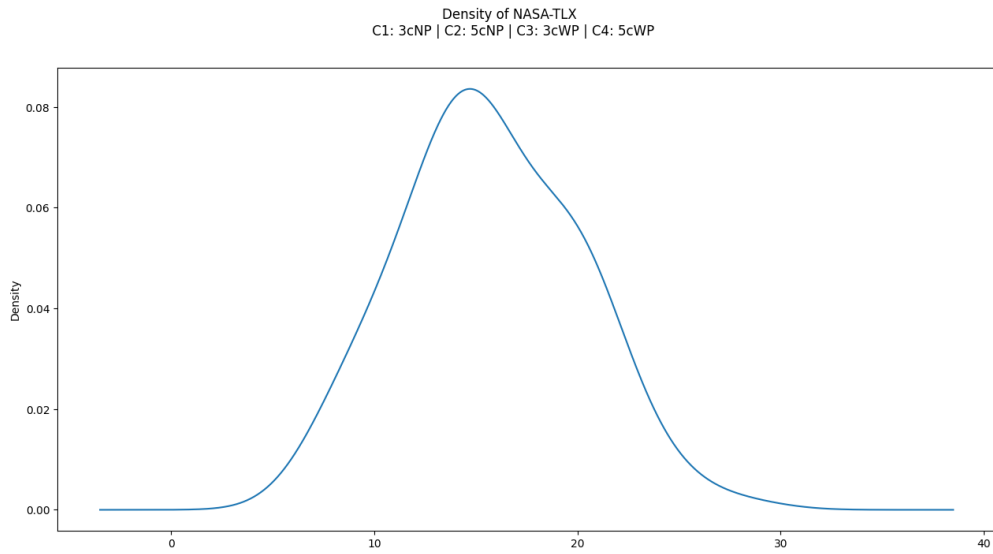


Figure 6.21 – Repartition of NASA-TLX scores from the user study presented in Chapter 5.

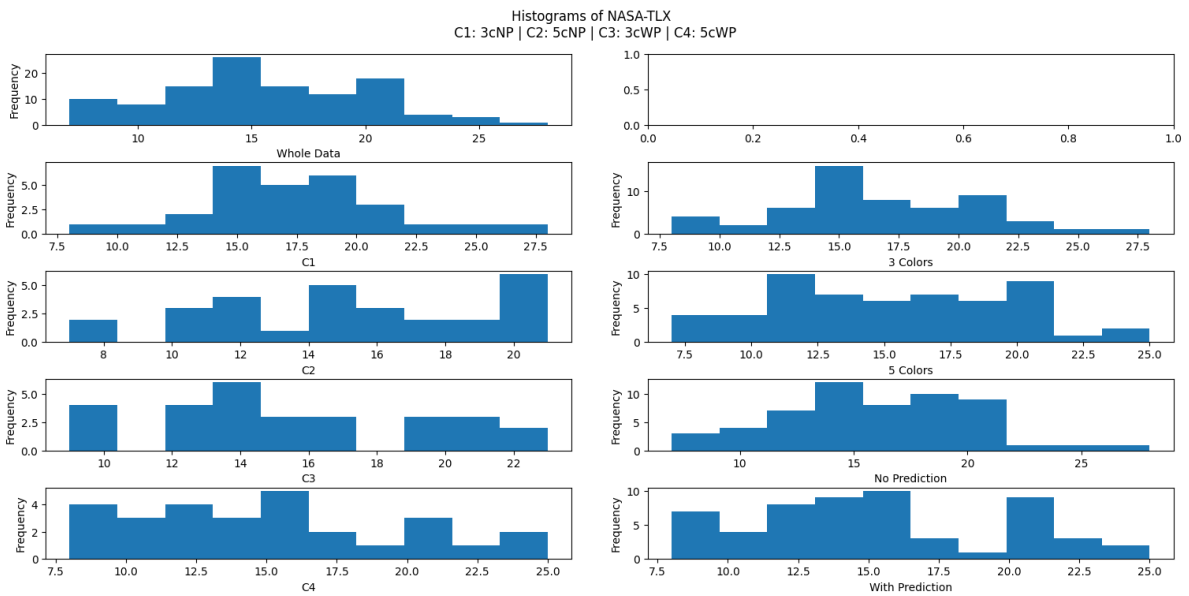


Figure 6.22 – Repartition of NASA-TLX scores among conditions from the user study presented in Chapter 5.

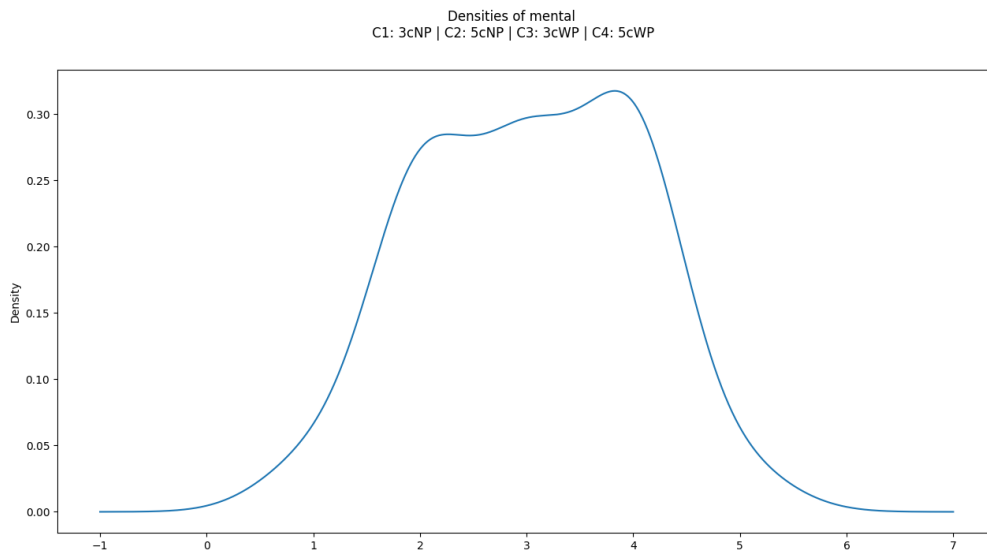


Figure 6.23 – Repartition of Mental Demand scores from the user study presented in Chapter 5.

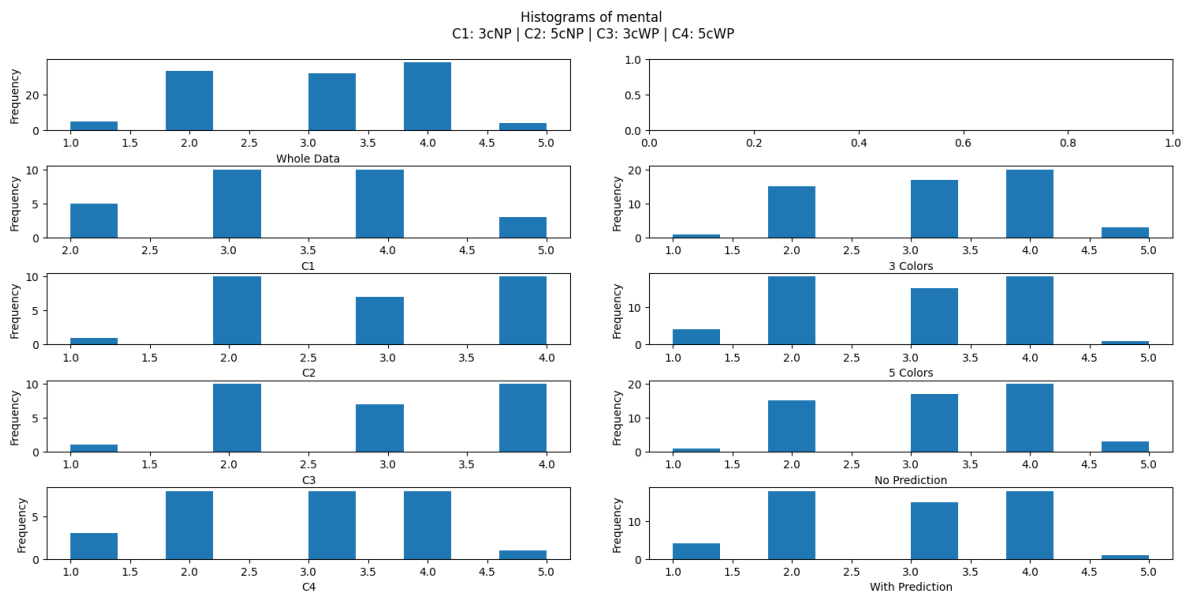


Figure 6.24 – Repartition of Mental Demand scores among conditions from the user study presented in Chapter 5.

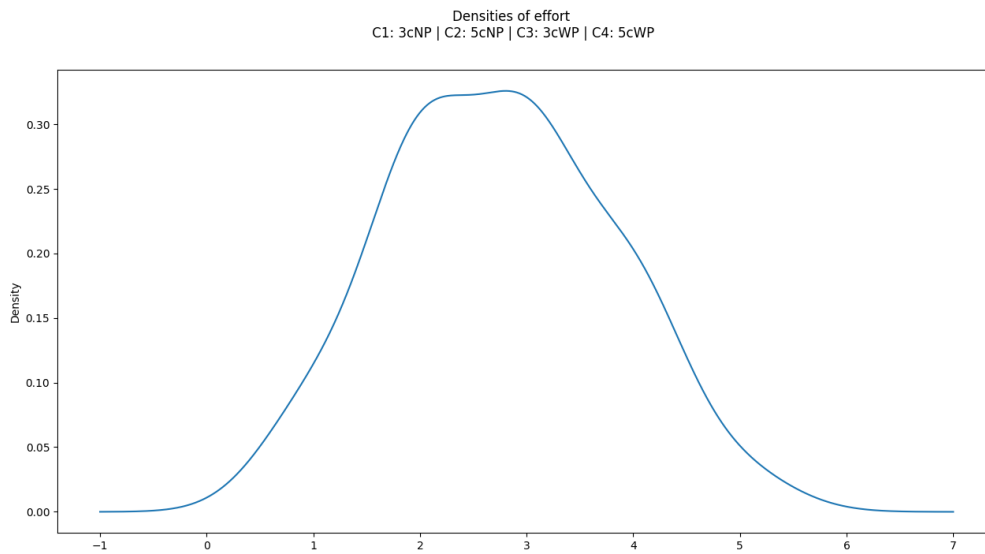


Figure 6.25 – Repartition of Effort scores from the user study presented in Chapter 5.

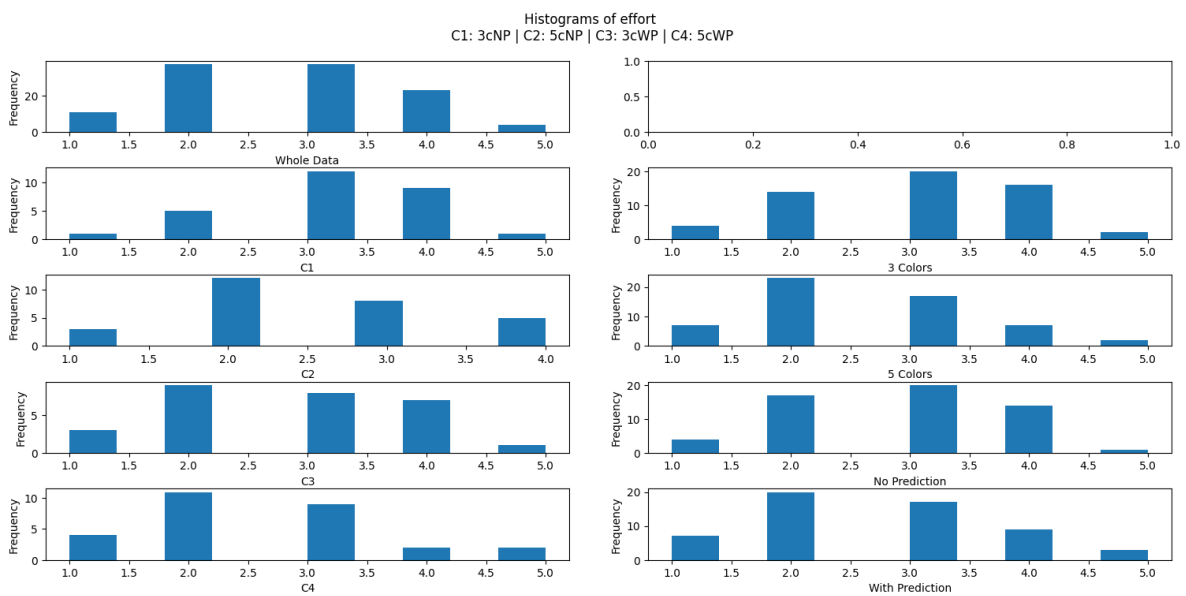


Figure 6.26 – Repartition of Effort scores among conditions from the user study presented in Chapter 5.

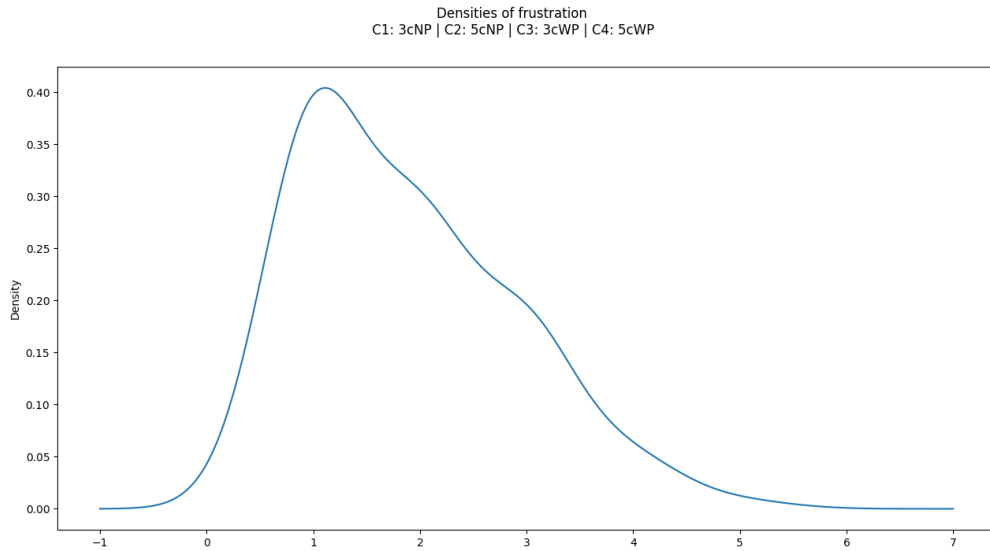


Figure 6.27 – Repartition of Frustration scores from the user study presented in Chapter 5.

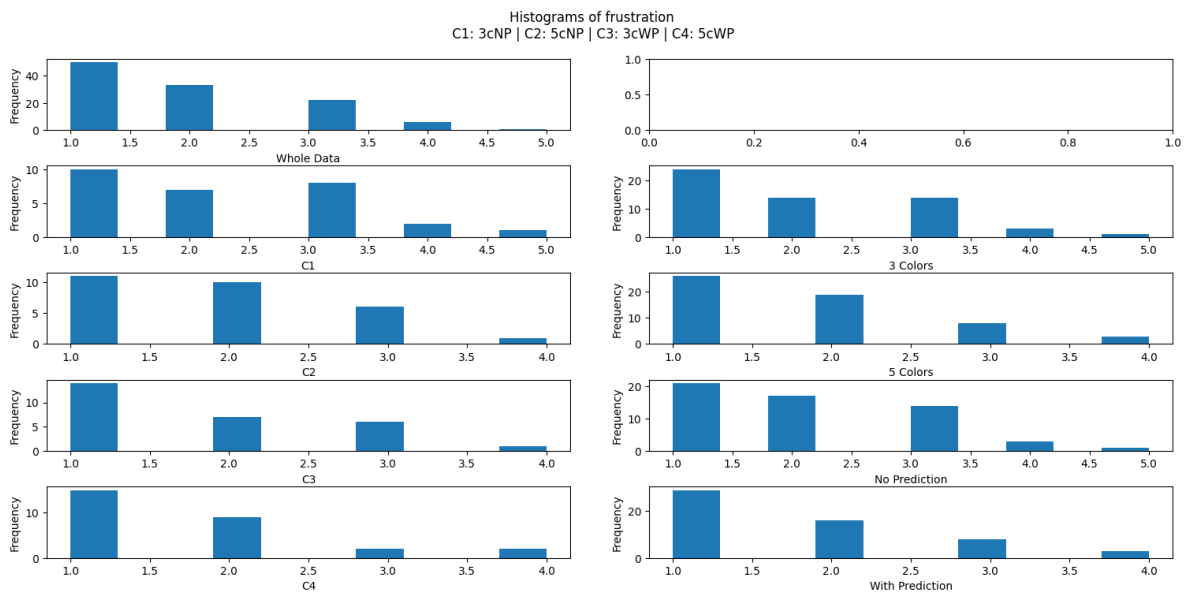


Figure 6.28 – Repartition of Frustration scores among conditions from the user study presented in Chapter 5.

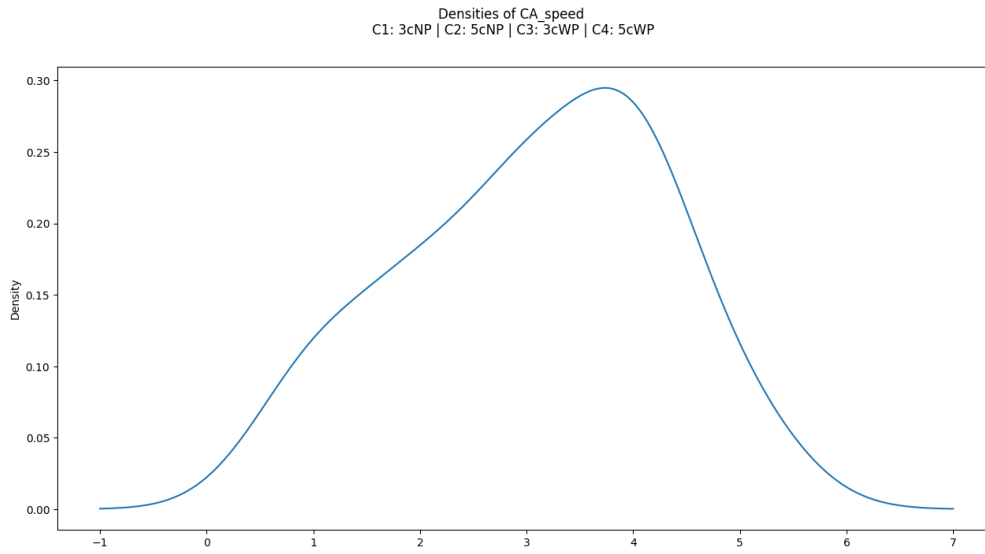


Figure 6.29 – Repartition of participants self evaluation of their ability to identify slow and fast operators during the user study presented in Chapter 5.

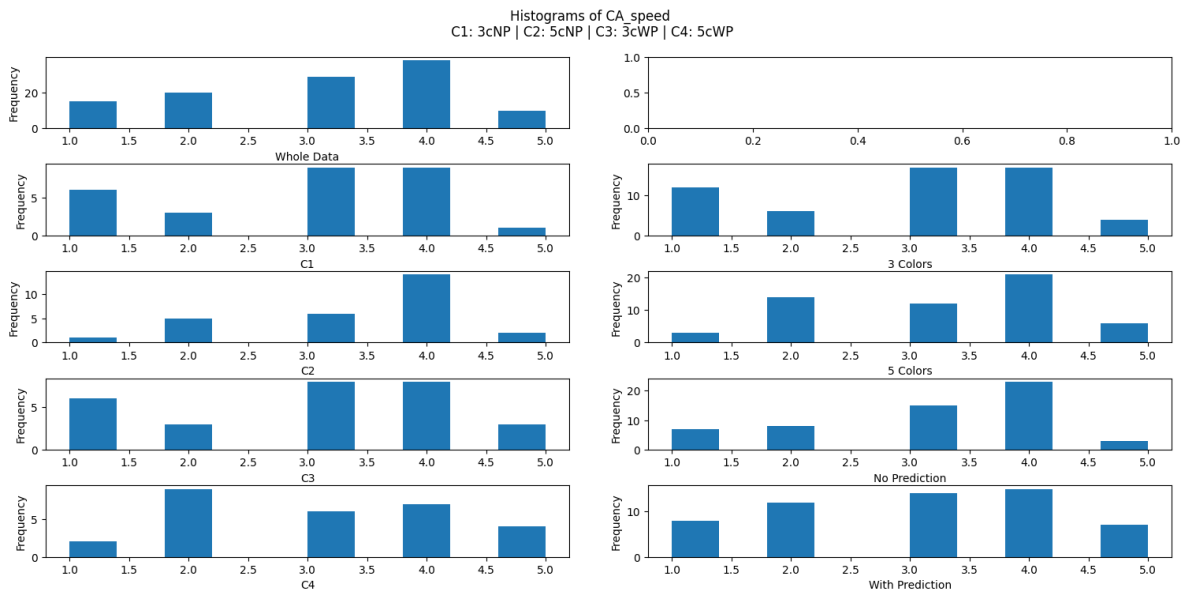


Figure 6.30 – Repartition of participants self evaluation of their ability to identify slow and fast operators during conditions from the user study presented in Chapter 5.

PERCEPTION DES ACTIVITÉS COLLABORATIVES PAR LA RÉALITÉ ÉTENDUE - Thomas RINNERT Ph.D

Résumé long

Cette dissertation présente un travail sur la collaboration et la perception des activités collaboratives par les personnes dans des environnements améliorés par les technologies de Réalité Étendue (XR). La collaboration est un domaine crucial, car travailler ensemble peut améliorer l'efficacité et la productivité. La base du travail collaboratif est de rassembler chaque membre au même endroit et de réaliser des tâches ensemble, en partageant des idées et des compétences tout en étant physiquement et/ou virtuellement proches les uns des autres.

Pour permettre aux gens de continuer à travailler conjointement malgré la distance, les dispositifs et technologies de communication numériques offrent plusieurs niveaux de présence. Avec les avancées technologiques, la réduction de la latence et l'adoption croissante, la technologie devient de plus en plus répandue et de meilleure qualité. Cependant, dans les espaces de travail collaboratifs tant en colocalisation qu'à distance, les membres des équipes privilégient souvent les activités axées sur les tâches, au détriment d'une compréhension globale de la dynamique de travail, ce qui entraîne un risque de négliger des indices implicites, tels que la fatigue, le stress ou les malentendus entre membres de l'équipe. Les espaces de travail partagés à distance actuels, malgré leurs avancées, peuvent contribuer à négliger ces indices subtils.

Cette dissertation concerne l'amélioration du travail d'équipe avec les technologies XR, que ce soit pour des équipes partageant physiquement le même lieu de travail ou des équipes travaillant exclusivement ou partiellement avec des membres à distance. Elle couvre ainsi une gamme d'espaces de travail XR tels que des environnements enrichis par la Réalité Augmentée (AR), des collaborateurs entièrement immergés à distance dans des environnements de Réalité Virtuelle (VR), ou de la Réalité Mixte (MR) avec des utilisateurs colocalisés et seulement une partie de leurs collaborateurs étant à distance en utilisant à la fois AR et VR.

Les environnements XR partagés peuvent être utilisés pour améliorer la compréhension mutuelle, guider, contrôler et coordonner les personnes dans de nombreux domaines tels que l'industrie du futur, la défense, la santé et l'éducation. Par exemple, l'industrie du futur peut être améliorée en partageant le statut des utilisateurs locaux avec des experts à distance pour les tâches de maintenance et d'exploitation technique, réduisant ainsi le temps et le coût des interventions. De même que pour l'industrie, les solutions proposées peuvent améliorer le téléguidage pour la maintenance et les opérations techniques pour la défense, mais aussi pour

le contrôle des missions afin de mieux surveiller les membres d'une escouade et de prendre de meilleures décisions de commandement. Ces augmentations peuvent également faciliter la communication pendant la planification de la stratégie, ou être appliquées à la communication centrée sur la tâche et l'équipe entre les analystes de la cyberdéfense et ainsi améliorer la collecte d'informations, l'identification des problèmes actuels et l'établissement de plans et de stratégies. Dans le domaine de l'éducation, les classes augmentées tirent parti de l'intégration d'objets virtuels dans des environnements réels, ce qui permet aux apprenants de visualiser des relations spatiales complexes et de saisir des concepts abstraits. Ces classes offrent la possibilité d'expérimenter des phénomènes autrement inaccessibles dans le monde physique, en facilitant l'interaction avec des objets synthétiques bidimensionnels et tridimensionnels dans une réalité mixte.

En ce qui concerne la santé, l'application de la XR présente un potentiel prometteur, à la fois pour améliorer le bien-être du grand public et la coordination entre les professionnels de la santé. Grâce aux visualisations XR permettant de partager les informations sur l'état des personnes, une nouvelle dimension de compréhension mutuelle peut être atteinte. Cette approche va au-delà des méthodes de communication conventionnelles, en fournissant un aperçu en temps réel et contextuel de l'état physique et mental des individus. Dans le contexte du grand public, la XR peut contribuer à privilégier un environnement de travail plus sain en offrant des informations personnalisées sur le bien-être. Les individus peuvent recevoir des informations opportunes sur des facteurs tels que la posture, les niveaux de stress et l'ergonomie, ce qui leur permet de prendre des décisions éclairées qui ont un impact positif sur leur santé et leur productivité globales. Pour les professionnels de la santé, l'intégration de XR facilite la communication et la collaboration. Le partage de l'état des médecins et des patients par l'intermédiaire des interfaces XR réduit le risque d'erreurs d'interprétation. Cet accès en temps réel à des données complètes garantit que les équipes de soins de santé sont bien informées, ce qui permet de poser des diagnostics plus précis, de prendre des décisions plus efficaces et, en fin de compte, d'améliorer les résultats pour les patients. En substance, l'utilisation de XR pour partager des informations liées à l'état de santé peut changer la façon d'aborder le bien-être au travail et la collaboration médicale.

Les solutions proposées dans la thèse sont conçues pour s'appliquer à l'ensemble du domaine de la réalité virtuelle, sans être spécifiques à la RA, à la VR ou à la MR. En effet, cette thèse propose d'utiliser les technologies XR pour augmenter les individus avec des visualisations de leur statut, englobant à la fois leurs performances et leur bien-être. Ces visualisations visent à permettre aux collaborateurs de mieux comprendre les individus augmentés, qu'il s'agisse de leur état lié à la tâche ou de leurs sentiments personnels, ce qui favorise une meilleure assistance mutuelle et permet aux collaborateurs de réagir efficacement. Tout au long de cette thèse, les évolutions potentielles du travail en équipe sont illustrées par des exemples de cas d'utilisation, centrés sur le travail symétrique et la répartition des tâches.

La collaboration se heurte souvent à des obstacles majeurs lorsque des personnes travaillent ensemble, qu'elles soient entièrement colocalisées ou au moins partiellement réparties, en manquant des indications implicites tels que la fatigue, le stress ou l'incompréhension mutuelle

des membres de l'équipe. En outre, la collaboration devient plus difficile dans un contexte distribué et, dans le pire des cas, ces indications implicites manquées peuvent entraîner l'échec de la tâche collaborative. Il est donc impératif de relever ces défis nombreux et complexes avant d'exploiter pleinement le potentiel de la XR en matière de soutien à la collaboration. En outre, les systèmes XR doivent combler le fossé entre la présence physique et la distance. Les systèmes XR doivent améliorer encore la collaboration, en reconnaissant qu'un espace de travail physique partagé a une valeur irremplaçable, et qu'au-delà de la possibilité de les voir, une compréhension plus approfondie des membres de l'équipe est nécessaire pour cette amélioration. Cette compréhension de ce qu'ils font et de la manière dont ils le font aide à comprendre les collaborateurs : il est donc nécessaire de pouvoir connaître leurs performances dans les activités passées et de savoir s'ils s'adaptent au travail. Ces performances passées et présentes peuvent être mesurées de différentes manières en fonction de la tâche attribuée au groupe, et le bien-être des collaborateurs doit être interprété à partir de diverses modalités, telles que l'état des individus, les gestes et les expressions faciales.

Ces idées et les défis qu'elles posent révèlent de multiples directions de recherche. Tout d'abord, l'étude d'une nouvelle architecture de réseau faciliterait le déploiement d'équipes distribuées complexes, qu'il s'agisse de grands groupes tels que les jeux en ligne massivement multijoueurs en réalité virtuelle (VRMMO) ou les rassemblements sociaux (par exemple, les conférences VR de l'IEEE pendant la pandémie), de groupes avec de multiples rôles non exclusifs impliqués et de la manière dont les personnes gèrent les interactions au sein d'un espace de travail collaboratif aussi riche en diversité de rôles, ou de groupes disposant de différentes technologies augmentatives ou immersives (par exemple, une équipe évoluant dans un espace de travail réel dont les membres éloignés disposent d'une reconstruction en 3D de cet environnement).

Deuxièmement, la définition, la mesure et la présentation des performances ont été explorées en permanence. En dépit de cette exploration approfondie, ces trois aspects peuvent encore être affinés. La définition de la performance est influencée par le contexte applicatif, ce qui a un impact sur sa mesure et sa présentation ultérieure. Il est possible d'explorer des approches innovantes pour mesurer les informations liées à la performance et établir des méthodes de présentation efficaces, d'abord dans des contextes expérimentaux, puis en appliquant ces approches à des scénarios d'application dans le monde réel.

Le troisième aspect concerne l'amélioration de la mesure de l'état des collaborateurs, en affinant la collecte et l'abstraction des données physiologiques sous forme d'étiquettes plus complètes afin de mieux comprendre leurs sentiments.

Enfin, l'analyse des mains, des bras, des gestes du corps entier et des expressions faciales peuvent améliorer la compréhension des autres membres de l'équipe, qu'elle repose sur des interprétations individuelles ou sur celles générées par des algorithmes d'intelligence artificielle (IA). Il est important de noter qu'il ne s'agit pas d'une liste exhaustive, mais plutôt d'un aperçu de certaines des questions les plus cruciales à l'heure actuelle.

Pour contribuer à ce domaine de recherche, cette thèse se concentre sur l'étude des moyens d'améliorer l'expérience de collaboration et d'approfondir la compréhension des actions, des comportements et des sentiments des uns et des autres. Pour ce faire, elle propose des approches novatrices dans le domaine de la XR afin de fournir aux utilisateurs des informations sur leur équipe, notamment sur les performances des membres et sur leur état interne, tel que le stress. Cet objectif a été motivé par l'importance de se comprendre mutuellement dans une équipe simple avant même d'envisager d'aborder les scénarios de collaboration complexes présentés ci-dessus. En ce qui concerne l'état des utilisateurs, diverses méthodes peuvent être employées pour recueillir des informations telles que la température corporelle ou le rythme cardiaque. La recherche sur la collecte et l'interprétation automatique des performances et des données physiologiques étant très prolifique, l'étude de la manière de présenter ces données est une approche importante pour contribuer au domaine du travail collaboratif assisté par ordinateur en réalité étendue (XR CSCW).

Cette thèse propose de présenter ces données en augmentant visuellement les corps ou les avatars des collaborateurs avec des informations sur leur performance et leur statut. La MATB-II de la NASA est un système bien étudié dont les performances de l'utilisateur sont facilement mesurables, et il est utilisé pour évaluer ces propositions par le biais d'expérimentations.

En effet, cette thèse se concentre principalement sur la présentation du statut des utilisateurs, reconnaissant que l'examen des méthodes de collecte et d'interprétation de ces données est un sujet vaste qui dépasse son champ d'application. Le terme « équipe » fait plus précisément référence au type de collaboration abordé dans ce manuscrit, qu'il s'agisse d'une équipe de travailleurs de même niveau s'occupant les uns des autres, ou d'une équipe de travailleurs sous la direction d'un superviseur. Dans ces types d'équipes, les membres ont des progrès communs, une performance d'équipe qui peut être mesurée et améliorée. Cette étude se concentre davantage sur la collaboration synchrone qu'asynchrone, même si, en termes de localisation, elle peut s'appliquer à la fois aux équipes colocalisées et aux équipes dont les membres sont éloignés.

Dans un espace de travail augmenté idéal, des informations pertinentes concernant les performances et le bien-être de chaque collaborateur seraient disponibles. En d'autres termes, les membres de l'équipe dont les performances sont satisfaisantes n'auraient pas d'augmentations visibles de leurs performances. En revanche, les personnes qui éprouvent des difficultés à maintenir leur niveau de performance habituel afficheraient des augmentations indiquant qu'elles ont besoin d'aide. Les personnes très performantes qui n'ont pas de tâches immédiates à accomplir auraient également une augmentation, signalant aux responsables de l'attribution des tâches qu'elles sont disponibles pour un travail supplémentaire. Cette vision d'un espace de travail augmenté vise à fournir des indicateurs clairs et contextuels, garantissant une communication et une coordination sans faille entre les membres de l'équipe. L'intégration d'augmentations qui fournissent des informations sur le bien-être des individus — couvrant le stress, la fatigue, la charge de travail cognitive et au-delà — constitue une mesure préventive précieuse. Cette approche permet de discerner le moment où une assistance peut être nécessaire, même avant une baisse notable des performances. En particulier dans l'attribution

des tâches, il est essentiel de connaître le bien-être d'un membre de l'équipe ; confier un travail excessif à une personne qui n'est pas en bonne santé peut entraîner une augmentation du nombre d'erreurs et des échecs potentiels. À terme, la prédiction de l'évolution de l'état interne des travailleurs permettrait d'améliorer encore les performances globales de l'équipe et le bien-être des individus. En résumé, un tel système permettrait une meilleure compréhension mutuelle et conduirait donc à de meilleurs résultats en matière de collaboration.

Cette dissertation aborde des questions de recherche qui contribuent au travail collaboratif assisté par ordinateur et aux domaines de la réalité étendue. Tout au long du manuscrit est présentée la manière dont ces questions ont été abordées et les solutions qui ont été choisies pour y répondre.

QR1 - Comment le partage du statut des utilisateurs avec la XR améliore-t-il la collaboration ?

L'exigence initiale d'améliorer le travail collaboratif avec la XR impliquait une exploration des augmentations qui pourraient être présentées parmi les collaborateurs et une compréhension de la façon dont elles affectaient l'expérience de collaboration. La première étude de cette thèse vise à déterminer si la perception du statut des utilisateurs peut contribuer à améliorer l'assistance mutuelle et la performance globale de l'équipe. Au cours de ces investigations, la recherche discerne quels aspects des données sur le statut de l'utilisateur sont les plus utiles pour détecter et caractériser le besoin d'assistance, conduisant finalement à une meilleure performance de l'équipe.

QR2 - Quels sont les éléments qui aident les chefs d'équipe à comprendre le statut des membres de leur équipe et comment les présenter ?

Répondre à cette question de recherche pourrait par exemple améliorer la détection et la caractérisation du besoin d'aide d'un individu, et le partage du statut des travailleurs pourrait potentiellement aider un chef d'équipe à mieux répartir les tâches au sein de son équipe. Nous avons donc mis en œuvre un cas d'utilisation à des fins expérimentales, impliquant un chef d'équipe assignant des tâches à des opérateurs, et demandant au chef d'équipe d'optimiser la performance globale de l'équipe. Là encore, plusieurs éléments de retour d'information ont été développés et la pertinence de chacun d'entre eux a été étudiée. Une étape supplémentaire a consisté à fournir un retour d'information sur l'évolution potentielle de l'état et à étudier la manière dont il aide les chefs d'équipe à prendre de meilleures décisions.

QR3 - Comment les données doivent-elles être abstraites pour mieux comprendre le statut des membres de l'équipe ?

En accord avec les questions de recherche précédentes, cette thèse étudie le niveau de détail et le style de présentation optimaux pour améliorer le travail d'équipe par le biais d'informations partagées. L'étude s'est penchée sur la question de savoir si les données brutes provenant des capteurs et des attributs du système devraient être directement partagées ou s'il serait plus avantageux de les abstraire derrière des niveaux distincts de « bon » et de « mauvais ». Les investigations ont également porté sur les avantages potentiels d'une approche hybride, combinant les deux stratégies. Cet aspect critique a été traité de manière approfondie dans l'ensemble de cette thèse, ce qui en souligne l'importance. Toutefois, il convient de poursuivre

l'exploration et l'affinement, en reconnaissant la complexité et la dépendance à l'égard du contexte des solutions potentielles.

Afin d'améliorer le niveau de conscience des collaborateurs, cette dissertation propose d'ajouter des indices d'information sur leur état émotionnel et physiologique, ainsi que des indices d'information sur la tâche de collaboration qu'ils doivent accomplir. Des métaphores visuelles adéquates de l'état des membres de l'équipe et de la performance de la tâche sont proposées pour comprendre les activités en cours à partir de la surveillance passive de leurs actions et de leurs comportements. Ces métaphores visuelles sont validées par une série d'études sur les utilisateurs afin de déterminer l'efficacité de ces indications pour détecter le besoin d'aide et équilibrer la charge de travail lors de l'attribution des tâches aux membres de l'équipe.

Ce mémoire explore diverses solutions visuelles visant à améliorer le travail d'équipe, en abordant des aspects clés, tout en reconnaissant que la couverture n'est pas exhaustive. L'accent est mis sur l'amélioration de la compréhension mutuelle entre les membres de l'équipe en étudiant le partage du feedback sur leur statut, afin de faciliter la détection des besoins d'assistance. En outre, la thèse étudie l'impact du partage des performances et des états internes sur les performances globales du travail d'équipe. Dans les scénarios de collaboration continue, où les membres de l'équipe peuvent interagir avec le travail de chacun, la thèse explore les avantages du partage de l'état actuel des performances et des informations sur la progression. De plus, la thèse examine les implications de la fourniture de prédictions sur l'évolution du statut des membres de l'équipe aux chefs d'équipe, en explorant son influence sur la performance et les stratégies de gestion. En ce qui concerne le style de présentation des indicateurs visuels, cette thèse suggère de considérer les deux extrémités de l'axe littéral-symbolique. La présentation de données littérales et non abstraites apporte la précision nécessaire à des mesures facilement compréhensibles, tandis que les symboles peuvent apporter la clarté ou l'abstraction nécessaire à des valeurs plus complexes. La thèse aborde le défi consistant à déterminer le niveau optimal de détail lors de l'abstraction d'informations, moins de détails entraînant une plus grande abstraction. Elle propose des étapes initiales pour trouver un niveau optimal dans ce contexte.

Des techniques de visualisation XR ont été mises en œuvre pour présenter les performances et l'état interne des utilisateurs, ce qui permet de partager ces informations avec d'autres personnes. Les visualisations proposées ont été regroupées et présentées sur un panneau relatif au corps, situé sur l'avant-bras des utilisateurs pour une référence pratique, un peu comme une montre intelligente. Par ailleurs, certaines visualisations ont été réparties entre tous les membres de l'équipe sur des panneaux flottants. Les visualisations proposées ont été examinées à différents niveaux d'abstraction. Pour évaluer ces propositions, une plateforme expérimentale a été modélisée et prototypée dans un environnement immersif, avec un système MATB-II adapté de la NASA et des modèles de travailleurs virtuels pour étudier la gestion d'équipe. Un premier prototype a été fourni par Jamie Gower, doctorant à l'UniSA, contenant une version mono-utilisateur de l'adaptation VR de MATB-II. La plateforme expérimentale, disponible en tant qu'artefact de recherche, peut être consultée à l'adresse https://github.com/ThomasRinnert/MATB-II_CollabVR. Elle présente des scènes de

collaboration symétrique et de gestion d'équipe. Toutes les visualisations évaluées sont incluses dans ce dépôt.

Les contributions décrites dans cette thèse ont fait l'objet d'une évaluation rigoureuse par le biais d'études sur les utilisateurs. L'efficacité de la fourniture d'un retour d'information sur l'état de la tâche pour améliorer la détection du moment où un collaborateur a besoin d'aide a été validée dans l'étude initiale décrite au chapitre 3. En outre, cette étude a confirmé que les membres de l'équipe préféraient se concentrer sur l'état actuel des performances plutôt que sur les informations relatives à la progression. L'impact positif du partage de l'état interne des membres de l'équipe sur la performance de l'équipe a été démontré par une deuxième étude, détaillée au chapitre 4. Cette étude a également confirmé la tendance des chefs d'équipe à préférer le statut interne des membres de leur équipe à un niveau d'abstraction plus élevé. Les réactions des participants à cette étude ont montré les avantages des présentations littérales et symboliques, soulignant l'importance de fournir des informations à la fois brutes et abstraites pour répondre aux diverses préférences. Les résultats d'une troisième étude, détaillés au chapitre 5, ont validé le fait que la prédiction de l'évolution du statut interne des membres de l'équipe influençait positivement la performance de l'équipe. Cette étude a également validé le fait qu'une plus grande précision dans le statut interne des membres de l'équipe aide les dirigeants à optimiser la performance de l'équipe.

Cette thèse a abordé les limites identifiées de la littérature concernant la conscience de collaboration, en particulier en ce qui concerne la présentation des données d'état disponibles et l'amélioration de la compréhension mutuelle. Les investigations ont exploré les méthodes de partage des informations sur le statut entre les membres de l'équipe et leurs dirigeants afin d'améliorer les résultats de la collaboration. Cette dissertation se développe en trois actes progressifs, chacun s'appuyant sur les fondements posés par le précédent.

Le premier acte a étudié l'impact du partage de statut entre les travailleurs de niveau égal sur la conscience de collaboration. À plus grande échelle, le deuxième acte a retracé les recherches sur le partage du statut des membres de l'équipe avec leur chef afin d'améliorer leur processus d'attribution des tâches. Le troisième acte propose de présenter le statut prédit des membres de l'équipe à leurs chefs dans le but d'améliorer encore leur processus de répartition des tâches. Ainsi, cette thèse contribue méthodologiquement et expérimentalement à la conception de futurs espaces de travail en XR avec une meilleure conscience de collaboration.

La première contribution a été d'améliorer la conscience de collaboration des travailleurs en poursuivant l'objectif d'accroître la compréhension mutuelle et la capacité à s'entraider. Cette première investigation s'est concentrée sur la collaboration symétrique et synchrone afin d'étudier l'impact du partage du statut de chacun dans un contexte de collaboration de petite taille. Plusieurs indicateurs du statut d'un collaborateur sont donc proposés, que ce soit à des fins d'identification ou de partage du statut de la tâche et du statut interne. Ces indicateurs donnent des informations sur les valeurs passées et actuelles du système ou sur le bien-être du collaborateur. Bien que les indicateurs du statut de la tâche et du statut interne aient été proposés, l'expérience menée avec vingt participants s'est concentrée sur l'évaluation de

l'impact du statut de la tâche sur la performance et sur l'efficacité et l'occurrence de l'entraide. Cette étude sur les utilisateurs a démontré que le fait de donner des informations sur le statut de la tâche améliore la détection du besoin d'aide et que les gens préfèrent les informations instantanées à un historique de la progression dans de tels contextes de collaboration. Le partage de ces indicateurs d'état des tâches entre les membres de l'équipe s'avère donc utile pour améliorer la conscience de la collaboration entre les membres de l'équipe dans le cadre d'une collaboration symétrique et synchrone. Sur la base de ces résultats, l'étape suivante consisterait à évaluer leur efficacité dans différents contextes de collaboration, ce qui a été étudié dans les enquêtes ultérieures.

Explorant la collaboration à plus grande échelle, la deuxième contribution a amélioré les résultats de la collaboration en fournissant aux chefs d'équipe un retour d'information sur l'état de leurs membres. Dans un contexte dans lequel le chef d'équipe doit surveiller les travailleurs, une collaboration efficace exige non seulement de percevoir les positions et les actions des partenaires, mais aussi de comprendre leur état (activité, état émotionnel, fatigue, etc.), ce qui est encore plus crucial pour les chefs d'équipe lorsqu'ils assignent du travail aux membres de leur équipe. Le processus d'attribution des tâches à une équipe de travail a donc été amélioré grâce au retour d'informations sur le statut de la tâche et le bien-être des membres. Pour le statut de la tâche, des indicateurs sur les états passés, présents et futurs des tâches assignées à chaque travailleur sont proposés, et pour le statut interne d'un travailleur, un autre indicateur d'une mesure unique du bien-être étiqueté comme « stress » est proposé pour la compréhension du grand public. Tous les indicateurs ont été mis en œuvre selon deux modes de présentation : 'Littéral' affichant des informations aussi brutes que possible avec des mots et des chiffres écrits ; et 'Symbolique' avec des abstractions telles que des icônes, des graphiques ou des artefacts en 3D. Une expérience menée avec vingt-quatre participants a permis d'évaluer la pertinence de chaque indicateur et leur efficacité à améliorer les résultats de la collaboration. Cette étude a révélé qu'une présentation non abstraite de statut interne permettait d'améliorer les performances de l'équipe, même si les participants préféraient une présentation avec des symboles abstrayant les données. En outre, cette contribution met en évidence l'importance du partage des informations sur l'état interne entre les membres de l'équipe, en particulier dans le contexte de la surveillance d'une équipe de travailleurs. Toutefois, étant donné que les présentations 'Littéral' et 'Symbolique' présentent toutes deux des avantages distincts et que certains indicateurs sont plus performants avec l'une ou l'autre, des recherches supplémentaires sont nécessaires pour déterminer le niveau d'abstraction optimal pour chaque indicateur d'état.

En affinant les résultats de la contribution précédente, la présentation du statut interne a été approfondie. Comme l'ont suggéré les résultats des deux contributions précédentes, la fourniture d'informations sur l'état actuel et futur mérite d'être étudiée plus en profondeur. Comme les travaux connexes montrent que la prévision de l'évolution du statut interne est possible, bien que complexe, cette contribution explore l'impact de la présentation d'une telle prévision aux chefs d'équipe sur les résultats de la collaboration. Il est donc proposé de fournir aux chefs d'équipe une prédiction du statut interne de leurs travailleurs après qu'ils aient accompli toutes les tâches qui leur ont été assignées. Cette prédiction était présentée sous la

forme d'un halo flottant placé autour de la tête d'un travailleur, le niveau de statut interne étant indiqué par des couleurs. Pour évaluer cette proposition, une expérience a été menée avec vingt-huit participants afin de déterminer l'impact d'une telle prédiction sur les résultats de la collaboration et d'entamer une recherche sur le meilleur niveau d'abstraction des indicateurs proposés. Les résultats de cette expérience ont montré que la présentation de cette prédiction avec un niveau d'abstraction plus léger, c'est-à-dire avec plus de niveaux distincts, conduit à une performance encore meilleure et est préférée par les personnes à qui elle est présentée. En outre, les participants ont indiqué qu'ils préféreraient recevoir des prédictions sur l'évolution de l'état des membres de leur équipe plutôt que des informations sur l'état actuel, ce qui souligne la valeur potentielle de cette approche pour faciliter un travail d'équipe efficace. Cette contribution fait progresser l'étude de la pertinence du partage des informations sur le statut et explore le niveau d'abstraction optimal pour faciliter un travail d'équipe efficace tout en minimisant la confusion pour les chefs d'équipe.

Enfin, à des fins expérimentales, une plateforme open-source, disponible à l'adresse https://github.com/ThomasRinnert/MATB-II_CollabVR, a été développée pour faciliter la collaboration au sein des espaces de travail XR. Comme cette plateforme offre une grande capacité de personnalisation, elle a servi d'outil précieux pour valider les propositions scientifiques par l'expérimentation. En outre, cet outil extensible présente un potentiel important pour les recherches futures. À l'exception des études pilotes, trois expériences ont été menées à l'aide de cette plateforme pour étudier la collaboration dans les environnements XR :

- Une étude utilisateur sur le partage du statut de l'utilisateur pendant la collaboration synchrone (voir chapitre 3),
- Une étude utilisateur sur le suivi du statut des membres de l'équipe pour la répartition des tâches (voir chapitre 4),
- Une étude utilisateur sur le suivi d'une prédiction de l'évolution du statut interne des membres de l'équipe pour l'attribution des tâches (voir chapitre 5).

Bien que la dissertation se soit principalement concentrée sur les équipes colocalisées, les connaissances acquises sont transférables à divers scénarios de travail en équipe, y compris les collaborations à distance facilitées par les technologies XR. Par exemple, la plateforme expérimentale développée pour cette recherche a été utilisée dans une démonstration impliquant une collaboration entre des participants australiens et français. Cependant, il est important de reconnaître une limitation inévitable : la vitesse de la lumière et le réseau introduisent une latence entre les utilisateurs en France et en Australie. Bien que cette latence n'ait pas été prohibitive dans les contextes applicatifs abordés dans la dissertation, elle peut nécessiter une attention particulière dans des tâches de co-manipulation hautement critiques en termes de temps.

Les implications de ces recherches vont au-delà de la collaboration symétrique et des équipes simulées, incitant à réfléchir à leur mise en œuvre dans diverses industries. L'application de différentes présentations des informations de statut et des stratégies d'adaptation des équipes, telles qu'identifiées dans cette recherche, a le potentiel de redéfinir les pratiques de gestion des équipes. Cependant, il est essentiel de reconnaître les implications du déploiement de telles

technologies dans des situations réelles, notamment les préoccupations éthiques entourant le partage de données privées, le risque de pression managériale conduisant à l'épuisement professionnel des employés et la charge cognitive résultant des changements dans les habitudes de travail.

Comme tout outil puissant, la mise en œuvre de retours d'information sur l'état interne des utilisateurs et des stratégies d'adaptation pour les équipes doit être abordée de manière réfléchie et éthique afin d'éviter tout usage abusif potentiel. Il est important de reconnaître qu'il n'existe pas de solutions universelles ; c'est plutôt l'application responsable et éclairée de ces connaissances qui permettra d'obtenir des résultats positifs dans les environnements de travail réels. En effet, la mise en œuvre de retours d'information sur l'état interne des utilisateurs pour les chefs d'équipe pourrait améliorer la performance de l'équipe et contribuer au bien-être global des membres. Cela implique une évolution vers une approche plus empathique du travail en équipe, qui pourrait se révéler précieuse dans les secteurs où la fiabilité des performances avec un minimum d'erreurs est cruciale. Néanmoins, nous reconnaissons que la mise en pratique de ces techniques présente des défis.

Bien sûr, dès que des personnes réelles sont impliquées dans de tels contextes, des problèmes éthiques devront être abordés. Le partage de l'état des utilisateurs doit respecter les règles de confidentialité et d'éthique, et doit nécessiter le consentement des personnes surveillées. Comme l'ont indiqué les participants aux expérimentations rapportées, la prédiction de l'état interne des utilisateurs est encore plus utile pour l'affectation des tâches que la réception d'informations sur l'état actuel des membres de l'équipe. Cela pourrait constituer le début d'une solution pour répondre à la question éthique du partage de l'état des personnes, avec une estimation future de l'état interne intégrée implicitement dans un algorithme conseillant les chefs d'équipe sur l'affectation des tâches, sans divulguer explicitement de détails spécifiques sur l'état des travailleurs. Si un système ne fournit qu'une prédiction de l'état des personnes lorsqu'elles sont à risque, pour leur propre bien-être afin de ne pas leur mettre plus de pression, ce système serait moins intrusif que ce qui est actuellement proposé dans la littérature et déployé dans l'industrie.

En outre, des facteurs tels que l'adaptation des mécanismes de retour d'information aux besoins spécifiques de l'industrie, la gestion de la résistance potentielle au changement et l'intégration de ces techniques dans les flux de travail existants doivent être pris en compte. Des recherches supplémentaires et une collaboration avec des professionnels de l'industrie pourraient fournir des informations précieuses pour surmonter ces défis et optimiser l'application des contributions de ma dissertation dans des environnements de travail réels.

Enfin, il est essentiel de reconnaître que le travail en équipe va au-delà de la seule interaction humaine. Avec l'intégration croissante de la technologie dans les environnements de travail, les équipes sont souvent composées à la fois d'humains et de machines collaborant. Bien que les machines ne possèdent pas les mêmes mesures nuancées de l'état que les humains, des métriques équivalentes peuvent être conçues et explorées. Cette perspective plus large souligne la nécessité de cadres adaptables englobant à la fois les éléments humains et machines au sein des environnements collaboratifs.

Titre : PERCEPTION DES ACTIVITÉS COLLABORATIVES PAR LA RÉALITÉ ÉTENDUE

Mot clés : Réalité Étendue, Réalité Mixte, Réalité Augmentée, Réalité Virtuelle, Informatique Empathique, Conscience de la Collaboration

Résumé : Cette thèse se concentre sur l'exploitation des technologies de Réalité Étendue (Extended Reality, XR) pour améliorer le travail d'équipe, que les équipes partagent un espace physique ou travaillent à distance. S'appuyant sur des travaux antérieurs dans le domaine du travail collaboratif assisté par ordinateur (CSCW), les contributions présentées dans cette thèse abordent un large spectre d'environnements XR, les Réalité Augmentée (RA), Virtuelle (RV) et Mixte (RM), adaptées à divers domaines tels que l'industrie 4.0, la défense, la santé et l'éducation. Les solutions proposées visent à augmenter les individus avec des visualisations qui dépeignent à la fois leur performance et leur bien-être, facilitant une meilleure compréhension entre les

collaborateurs, et leur permettant de répondre efficacement aux besoins de chacun et favorisant l'assistance mutuelle. La thèse se déroule en trois actes : premièrement, l'étude de l'impact du partage du statut entre pairs sur la sensibilisation à la collaboration ; deuxièmement, l'exploration des avantages du partage du statut des membres de l'équipe avec les chefs pour améliorer la répartition des tâches ; et enfin, la proposition de la présentation du statut prédit des membres de l'équipe aux chefs pour une optimisation supplémentaire de la répartition des tâches. Les contributions méthodologiques et expérimentales présentées visent à éclairer la conception des futurs espaces de travail XR avec une conscience accrue de la collaboration.

Title: PERCEIVING COLLABORATIVE ACTIVITY WITH EXTENDED REALITY

Keywords: Extended Reality, Mixed Reality, Augmented Reality, Virtual Reality, Empathic computing, Awareness of Collaboration

Abstract: This dissertation focuses on leveraging Extended Reality (XR) technologies to enhance teamwork, whether teams share a physical space or work remotely. Building upon previous work in Computer-Supported Collaborative Work (CSCW), the contributions presented in this dissertation address a large spectrum of XR environments, including Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR), tailored for diverse domains such as Industry 4.0, Defense, Health, and Education. The proposed solutions aim to augment individuals with visualizations that depict both their performance and well-being, facilitating better understanding among collab-

orators, enabling them to respond effectively to each other's needs and fostering mutual assistance. The dissertation unfolds in three acts: firstly, investigating the impact of sharing status among peers on collaboration awareness; secondly, exploring the benefits of sharing team members' status with leaders to enhance task allocation; and finally, proposing the presentation of predicted team members' status to leaders for further optimization of task allocation. The presented methodological and experimental contributions are made to inform the design of future XR workspaces with a heightened awareness of collaboration.